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Dynamic Test of Bridges in Ontario, 1980: Data Capture, Test Procedures, and Data Processing

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ABSTRACT

A program of dynamic tests of bridges was undertaken by the Ontario Ministry of Transportation and Communications (MTC) in 1980. This program was in support of the second edition of the Ontario Highway Bridge Design Code. Twenty-six bridges were tested, having spans from 5 m (16 ft.) to 66.4 m (218 ft.). They had a diversity of structural arrangements, and they ranged from two to fifty years in age. The bridges were selected to be typical of the population of existing bridges and current styles of construction in Ontario.

The test program followed a standard pattern for each bridge. This report presents those aspects of the test program which were common to all bridge tests and is a companion volume to the individual bridge test reports.

This report describes the instrumentation used, the FM multiplex data acquisition system, the test vehicles, the test procedures, and procedures for processing data captured in the tests.

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1/ INTRODUCTION

The first edition of the Ontario Highway Bridge Design Code was published in 1979 [1]. The Section of the Code on Dynamics and Vibration reflected earlier tests done by MTC and insights gained into the nature of bridge responses to heavy vehicles [2, 3]. The Section attempted to represent the principal characteristics of vehicle and bridge interaction, and also imposed a deflection limitation based on vibration as a serviceability limit state. These Code provisions were a considerable departure from prior practice and caused some difficulties for designers using them in early applications of the Code. A particular difficulty occurred for the deflection limitation, as it was developed on a rational basis for actual bridge responses, yet the design process generally could not provide a realistic deflection for comparison with the Code provision.

Review of the Code calibration process and early use of the Code identified the need for a better understanding of bridge responses to traffic. A program was therefore defined in 1980 to gather data by testing typical bridges and to process that data to provide the information necessary to determine and support Code provisions.

Twenty sites were selected for bridge dynamic tests, five of which were twin bridges. An additional dynamic test was already scheduled for another project, so inclusion of this provided a total of twenty-six bridges. These bridges represented many of the types frequently seen and currently constructed in Ontario, in typical span ranges and configurations. Bridges of concrete, steel, and timber construction, having spans from 5 m (16 ft.) to 66.4 m (218 ft.) in length, and from simple spans to ten continuous spans, were selected for testing. Even with twenty-six bridges, it was still only a limited sample of the multitude of types and configurations to be seen in Ontario. An additional test was added in 1981 [4].

Most of the bridges were selected following an inspection of bridges on the King's Highways in an area roughly bounded by London, Bracebridge, Ottawa, and Kingston. The list was culled by discarding bridges over obstructions such as navigable waterways, railroads, and highways whose

travelled lanes would interfere with instrumentation. Also discarded were bridges of unusual configuration and those having obvious impediments to test operations, such as difficult traffic control or an inadequate speed limit. The remaining short list of some forty testable and typical bridges was then reduced to a practical number for the time available by ensuring that each major type, span range, and configuration was represented. Wherever possible, bridges were selected in contrasting pairs of similar construction such as continuous bridges of the same number of spans but with different span ratios. The bridges tested in this series are given in Table 1.

It was realized early that such an ambitious program of tests could only be carried out before the onset of winter if it was conducted in a standardized manner. Adequate instrumentation, data acquisition systems and support equipment, together with experienced field technicians, were already available as MTC has been testing bridges for over ten years [5]. The main requirements, therefore, were to set up the instrumentation and data acquisition systems in as simple a way as possible, and to develop a testing procedure which could be followed for every test.

This report presents those elements of instrumentation, data capture, test and other vehicles, test procedures, and data processing, common to tests of all twenty-seven bridges. The individual bridge test reports [4, 6] all make reference to this report, and simply identify and describe any significant deviations from the standard elements described herein. The final section of this report presents some discussion and draws conclusions on the effectiveness of the equipment and procedures used in this series of tests.

Table 1/ Test Bridges

	Name	Construction	Spans	Skew
1	Shawanaga River Hwy 69	4 steel plate girders	1 simple, 36.576 m	None
2	Little Rouge Creek Hwy 7	6 AASHTO II girders	3 continuous 15.240-18.228-15.240 m	15°
3	Black River South Hwy 48	Timber	5 continuous, 4.039-4.877x3-4.039 m	None
4	Jock River Hwy 16	5 steel plate girders	1 simple 36.576 m	None
5	South Nation River Hwy 417	2 steel box girders	3 continuous 53.035-66.446-53.035 m	12°
6	Innisville Hwy 7	5 rolled steel girders	5 simple, 22.555 m each	None
7	Black River Hwy 7	4 reinforced concrete girders	2 simple, 15.850 m each	None
8	Millhaven Creek (EBL) Hwy 401	Rigid frame	1 rigid, 16.764 m	15°
9	Millhaven Creek (WBL) Hwy 401	Rigid frame	1 rigid, 16.764 m	15°
10	Palace Road (EBL) Hwy 401	8 rolled steel girders	1 simple, 16.801 m	46°27'
11	Palace Road (WBL) Hwy 401	8 rolled steel girders	1 simple, 16.801 m	46°27'
12	Eagleson's Road over Hwy 401	5 prestressed concrete girders	1 simple 41.377 m	39°42'
13	Baxter Creek Hwy 28	6 AASHTO II girders	1 simple, 16.459 m	None
14	Cavanville Creek Hwy 28	Prestressed concrete slab	3 continuous, 8.534-12.802-8.534 m	None
15	Pefferlaw Brook Hwy 48	8 AASHTO II girders	3 continuous, 12.192-21.336-12.192 m	10°
16	South Muskoka R. (NBL) Hwy 11	Deck truss	4 continuous, 7.620-20.523-30.785-7.696 m	None
17	South Muskoka R. (SBL) Hwy 11	3 steel box girders with stay legs	3 continuous, 25.908-36.576-25.908 m	None
18	Gull Lake (NBL) Hwy 11	4 steel plate girders	2 continuous, 48.768-48.768 m	None
19	Gull Lake (SBL) Hwy 11	4 steel plate girders	2 continuous, 48.768-48.768 m	None
20	North Muskoka R. (NBL) Hwy 11	5 steel plate girders	1 simple, 45.720 m	None
21	North Muskoka R. (SBL) Hwy 11	Through truss	1 simple, 45.720 m	None
22	Haultain's Hwy 28	Timber	10 continuous, 4.039-4.877x8-4.039 m	None
23	Townline Road over Hwy 402	4 precast concrete box girders	2 continuous, 30.480-30.480 m	None
24	Bostwick Road over Hwy 402	Prestressed concrete voided slab	2 continuous, 36.576-38.100 m	20°
25	Black River North Hwy 48	Timber	5 continuous, 4.039-4.877x3-4.039 m	None
26	Mississippi River Hwy 7	5 steel plate girders	5 continous, 21.336-27.432x3-21.336 m	None
27	Madawaska River Hwy 17	4 steel plate girders	3 continuous, 68.58-121.92-68.58 m	None

2/ INSTRUMENTATION

2.1/ Accelerometers

The Bruel and Kjaer Model 8306 seismic accelerometer was used. Its measuring element is a crystal in compression. It has a reference sensitivity at 50 Hz and 23°C of 10 V/g ± 2%; a maximum transverse sensitivity less than 5% at 6 Hz; and a frequency response varying less than 3db from unity between 0.1 and 1000 Hz. The accelerometer was mounted on a heavy steel base having three short pointed legs for stable placement on a rough surface. The mounted accelerometer has its first resonance in excess of 4500 Hz. The accelerometer was protected by a forged aluminum shield screwed to the base, into which is mounted a Switchcraft C5M chassis connector. A typical accelerometer is shown in Figure 1. A typical installation, with the accelerometer simply resting on the deck of a bridge, is shown in Figure 2.

An accelerometer was AC-coupled to a Burr-Brown Model 3620 amplifier, which also has a lower frequency limit of 0.1 Hz when its response is down 3db. The amplifier was packaged with a switchable gain and, with the signal conditioning modules used in the data acquisition system throughout the test program, the convenient levels of 0.5 g and 0.05 g full-scale were available.

2.2/ Electronic Displacement Transducer

The electronic displacement transducer was designed by BLH Electronics Inc. and was manufactured by North-East Materials Laboratory Inc. It has no model number, but is covered by U.S. Patent 3393556. The transducer has been used very successfully by MTC for bridge tests over a number of years but, as a result of heavy field use, it is gradually becoming less reliable.

The transducer consists of a spring-loaded moving rod of nominal 50.8 mm (2 in.) stroke, attached at one point to a strain-gauged endless loop around two wheels, as shown in Figure 3. Measurement of bridge deflection is accomplished by attaching the transducer body to a bracket weighted to the ground and attaching the moving rod to the bridge by means of an aircraft cable and a stud. A typical installation is shown

in Figure 4. The transducer bracket may also be clamped or bolted to the bridge, with the cable weighted to the ground. The spring load ensures about 45 N (10 lb.) tension in the cable. Care was taken to ensure that the transducer and cable were vertical, and the moving rod was positioned such that it would not bottom on the transducer body either for downward or upward bridge displacement. The nominal 50.8 mm (2 in.) stroke was in fact reduced to about 32 mm (1.25 in.) by Teflon collars at each entry of the moving rod into the transducer body, to protect the internal parts of the transducer from damage due to bottoming. The only problems with transducer mounting arose when the weight was slowly embedded in a soft river bottom due to its own weight and scour from the current. Wind and current evidently cause some vibration of the wire, but this has never been found to be a problem with these transducers.

The transducer has input and output impedances of 350 ohm, requires an excitation of 3 V, and is linear over its full range. The various transducers range in sensitivity from about 1.4 to 1.9 mV/V/in., so that the uncalibrated voltage outputs from a number of transducers on a structure can be somewhat misleading. Practical resolution of the transducer is 0.0254 mm (0.001 in.). The transducer's output lead is terminated in a Switchcraft C5M chassis connector for quick attachment to mating connectors on standard length cable bundles.

2.3/ Strain Gauges

The BLH Type SR-4 Model FAE-50-12-S6 uniaxial foil gauge, having a gauge factor of 2.02 ± 1%, a resistance of 120 ± 0.2 ohms, and a transverse sensitivity of - 1.2%, was used where conditions of other than axial strain might exist. This is shown in Figure 5. The BLH Type SR-4 Model FAET-25C-12-56 T-rosette foil gauge, having a gauge factor of 2.02 ± 1%, and a resistance of 120 ± 0.2 ohms, was used where conditions of pure axial strain existed.

Foil gauges were installed using standard procedures. The surface was prepared by a rough grinding to remove protective coatings, mill scale, and corrosion, then it was given a fine grinding to #150 grit. The gauge was bonded to the surface using a contact cement, and moisture-proofed by coating with a fast drying polyurethane. Lead wires were then soldered to the strain gauge tabs.

The Ailtech Model SG129-6S uniaxial weldable gauge, having flange length of 27.7 mm (1.09 in.), a gauge factor of 1.93 ± 3%, a resistance of 119 ohms, and a compensated temperature range of 0-180°F, was used in one case in lieu of the corresponding foil gauge due to cool temperatures.

Installation of the weldable strain gauge was similar to the foil gauge, except that its flange was spot welded to the surface.

The Wheatstone bridge for a simple gauge was completed using a dummy strain gauge on a steel tab. Dummies were made up in groups of four or six in a box, with each arm pair being terminated with a Switchcraft C5M chassis connector. Connection from the active gauge to the completion box was by a short wire, which connected to gold-flashed binding posts. The standard lead cables were then plugged directly into the box.

2.4/ Traffic Detectors

The lane of travel and speed of trucks was determined by means of standard pressure-activated switches used for traffic counting. The switches were connected to a sealed rubber tube nailed across the road. When a wheel crossed the tube, the pressure change activated a switch which resulted in an electrical pulse.

Four switches were used, in pairs, as two traffic detectors. A pair consisted of start and stop switches wired in series, with the start switch giving a positive pulse and the stop switch giving a negative pulse. The two pressure tubes were separated by 12.192 m (40 ft.), so vehicle speed could be estimated well within 1% at all legal speeds with a 100 Hz sample rate. Axles could be counted, but the error in estimation of axle spacing was significant.

One traffic detector was placed across each lane of a two-lane bridge. When a bridge had more than two lanes, one traffic detector was placed across each of the lanes most frequently used by heavy commercial vehicles. When twin bridges were tested simultaneously, one traffic detector was placed across all lanes of each bridge. A view of the traffic detector systems in place is shown in Figure 6.

3/ DATA CAPTURE

Instrument responses were taken by lead cable back to the MTC Mobile Laboratory shown in Figure 7. The cables were available both singly and as bundles of five in standard lengths of 15.2, 30.5, 61, and 152 m (50, 100, 200, and 500 ft.), as well as single cables in various short lengths. The cables were terminated in Switchcraft connectors at each end. It was a simple matter to plug a cable connector into the mating connector on an instrument, lead the cable through a small hatch in the rear of the Mobile Laboratory, and plug it into another connector on a patch panel adjacent to the hatch. Internal wiring joins this patch panel to another patch panel conveniently located behind a bench upon which the data acquisition system was mounted.

The data acquisition system was based upon the Metraplex 300 multi-channel constant bandwidth frequency-modulated multiplexing system. The system has considerable flexibility, but for this test program it was configured to multiplex 24 data channels, in three groups of eight, onto the first three tracks of a seven-track Honeywell Model 5600C instrumentation tape recorder. Time from a precision crystal-controlled clock, coded to give day, hours, minutes, and seconds, was provided by a Datum 9300 time code generator and was placed on the fourth track of the recorder. The voice track was used to identify the tape and the calibration segments. A control panel built by MTC provided various utility functions by means of push buttons and selector switches. It could be used to place various calibration signals on the tape; to route one of the three multiplex channels, either live or off the tape, to a bank of eight Metraplex 120 discriminators for display of the individual signals on a Honeywell Model 1858 eight-channel oscillograph; to route any individual signal to an oscilloscope; to select time code rate; and to route time code to the oscillograph. A view of the system is shown in Figure 8, and a schematic is shown in Figure 9.

Channel assignments of instruments were kept the same throughout the test program. The six accelerometers were always placed on the first six channels, and the two traffic detectors always followed them as channels seven and eight of Track 1. The sixteen channels of Tracks 2 and 3 were used for the bridge response channels, either electronic displacement transducers or strain gauges. Track 2 was monitored continuously on the

oscillograph. Instruments were assigned to this track which would define the duration of a vehicle on the bridge. For a twin bridge, when both bridges were tested simultaneously, Track 2 contained instruments from both bridges so that the duration of a vehicle on either bridge could be defined. Tracks 1 and 3 were checked from time to time during a test by selecting them on the oscillograph.

The multiplex system provided transducer excitation, signal conditioning, and calibration. The voltage signal from a transducer was lowpass filtered with a cut-off of 500 Hz to prevent aliasing, and was transformed to a frequency by a voltage controlled oscillator (VCO) such that ± full scale was represented by ± 500 Hz, and each channel on one track was shifted 2000 Hz from the previous one. Thus, a continuously varying voltage V(t) within the full scale range of ± 0.5 V on channel N results in a continuously varying frequency f(t) Hz given by:

$$f(t) = 2000\ N + 1000\ V(t).$$

Each channel of the data acquisition system was scaled by means of resistors on its signal conditioning card to provide the sensitivity appropriate to the full-scale instrument response specified by the test engineer. Each data channel could also be balanced so that the unloaded bridge gave zero VCO output, and scaled so that an artificially induced voltage of precisely 0.5 V gave 500 Hz VCO output. Setup of the multiplex system and electronic noise within the instruments and system resulted in an overall accuracy generally within 1% of full scale.

The tape recorder was run at a speed of 190.5 mm/s (7.5 in./sec.). This provided about 90 minutes of recording time when run continuously, or about a hundred vehicle passes when each pass was recorded individually.

4/ VEHICLES

Vehicles were classified according to configuration by the scheme shown in Figure 10, which has been used for various load surveys conducted by MTC. The classification scheme simply counts the number of axles in each unit of a vehicle and indicates the type of connection between tractor and trailer. Thus, 3S3 is a truck with a three-axle tractor and a three-axle semi-trailer, whereas 3-3 is a truck with a three-axle lead unit and a three-axle full trailer (i.e., a trailer which stands up when unhitched from the lead unit). Where a vehicle has three units, no distinction is made for the pup trailer, so a 3S3-2 has a two-axle pup but it is not known whether it is a full trailer (A-train) or semi-trailer (B-train) by the classification. The classifications shown in Figure 10 are not exhaustive, as vehicles such as 3S5 and 3S6 were observed during the test program. However, the classification scheme is sufficiently evident that the configuration of such unusual vehicles can be determined.

Five vehicles owned by MTC were used as known loads during various stages of the test program. These vehicles were given the identifications TV1, TV2, TV3, TV4, and TV5. TV1, TV2 and TV3 were tractor-trailer combinations loaded with standard 9.45 kN (2125 lb.) concrete blocks to near their legal limit. TV4 was a service vehicle used for installation of instrumentation which was also used as a load whenever it was present for a test. TV5 was an MTC water tanker which was used in only two early tests when it was present to provide protection to TV4.

TV1 was a Kenworth tractor with a King trailer of 3S2 configuration. A general view of this vehicle is shown in Figure 11. The trailer was equipped with a hydraulic crane and was capable of loading itself with concrete blocks to provide a known test load. The drive axles of TV1 were provided with leaf springs. The tandem axles of its trailer were also supported with leaf springs, as shown in Figure 12.

TV2 was a Mack tractor with a King trailer, also of 3S2 configuration. A general view of this vehicle is shown in Figure 13. The trailer was also equipped with a hydraulic crane and was capable of loading itself with standard concrete blocks. The drive axles of TV2 were also provided with leaf springs. The tandem axles of its semi-trailer were supported by

airsprings having shock absorbers in parallel, as shown in Figure 14. The airsprings and shock absorbers both provide significant damping to relative motions between the trailer and the axles.

TV3 was a White tractor with a King trailer and a King pup trailer. A general view of this vehicle is shown in Figure 15. The drive axles of TV3 were provided with leaf springs, as were the tandem axles of its semi-trailer. The lead axle of the pup trailer was a dolly with a leaf spring, whereas the second axle was an airlift with shock absorbers in parallel and the third was another leaf spring. The standard configuration of TV3 was 3S2-3, but it was also driven in configurations 3S2-2 with the pup airlift up, and 3S2 with no pup. This vehicle was also loaded with standard concrete blocks. TV3 is close to the maximum legal overall length for Ontario and could be loaded close to the 623 kN (140 000 lb.) maximum legal load for Ontario.

TV4 was the Inspector 50, a special purpose vehicle on a Mack chassis which was bought by MTC principally for inspection and maintenance of bridges. A general view of TV4 is shown in Figure 16. The vehicle has a bucket which has motion in five degrees of freedom and can reach up to 11.28 m (37 ft.) from the base of the arm, as shown in Figure 17. This capability made it invaluable for installation of instrumentation. The vehicle was also used as a load for test purposes, as it is representative in weight and axle spacing of an important class of vehicle, the three-axle dump truck. TV4 is of configuration 3, and has leaf springs on the drive axles.

TV5 was a standard MTC water tanker, and was used only in two early tests because it was available at the test site to provide protection to the rear for the Inspector 50 while it was working on a bridge. An overall view of TV5 is shown in Figure 18. The vehicle had three axles, configuration 3, and had a leaf spring on the drive axles. TV5 was found too light to cause significant bridge response so its use as a test load was discontinued.

TV1, TV2, and TV3 were loaded as close as practicable to their legal limits with the standard concrete blocks; TV4 had no payload capability; and TV5 was loaded to capacity with water. Each vehicle was weighed at

some time after every change of load, so individual axle loads were known for every test vehicle at every test. Dimensions of the test vehicles are shown in Figure 19.

Each test vehicle was equipped with a radio operating on a common frequency and having a range of 5-8 km (3-5 miles), depending on the terrain. The radio system was essential for control of the vehicles and safe conduct of the test.

Other vehicles were essential in support of the test. The data acquisition system was housed in the MTC Mobile Laboratory, previously shown in Figure 7. This vehicle is a specially modified motor-home and is equipped with a generator, air conditioning, work benches, a static data acquisition system (not used in this test series), a temporary installation of the data acquisition system described in the previous section, and tools and electronic components necessary to support the equipment. A 7.5 kW mobile diesel generator was used to power the Mobile Laboratory as it had greater endurance and reliability than the on-board generator. The generator was towed by a van which carried all of the bulky and heavy equipment required -- transducers, weights, cables, flags, signs, rope, etc. The job captain, whose role is described in the next section, used an MTC station wagon, equipped with the same type of radio as the test vehicles, as the control centre for the test. An MTC station wagon was also available to the Inspector 50 crew. Finally, local District staff had an MTC pick-up truck.

5/ TEST PROCEDURE

The test procedure was evolved from experience with a large number of bridge tests conducted successfully by MTC over the last eleven years [5]. The key to the successful and efficient test procedure lay in a clear statement of test requirements by the test engineer; a single individual responsible for planning, logistics, and conduct of the test; field technicians experienced with bridge testing; and proven instrumentation and auxiliary equipment, designed for field work, which was simple and easy to use.

Test requirements were provided by the test engineer on three sheets of paper, in a standard format. The first was a dimensional plan for location of the instrumentation, together with any special requirements to be observed or options available to the technicians. The second was an instrumentation table to be used as a worksheet to record transducer serial numbers and cable identities. The final sheet specified the runs to be made by the test vehicles, in terms of speed, direction, and driving lane. It also specified special vehicle configurations or multi-vehicle combinations. The test requirements were deliberately terse to avoid misunderstandings.

Organization and conduct of the test was the responsibility of the job captain. He reconnoitered the test site to identify a location for the Mobile Laboratory and turn-arounds for the test vehicles. He planned the test and made logistical arrangements including requisitions for vehicles and equipment and services such as District personnel, security guards, and police assistance. The job captain was responsible for the operation and safety of the test site which included the safety of both employees and the public. The job captain controlled all support vehicle movements and ordered all test vehicle runs according to the test run schedule. The test engineer was always present during the test to observe its conduct and bridge response, and to monitor the instrumentation output. If, during the course of a test, it became apparent that additional runs would be desirable, or specified runs were unnecessary, or some correction was necessary to instrumentation or test vehicle run schedule, then the test engineer advised the job captain of the changes. The job captain then modified the test procedure in such a manner that

elapsed test time was minimized. The latter was a priority, because conduct of the test did cause some disruption to traffic flow. The job captain was generally outside the Mobile Laboratory, and was provided with an intercom system to communicate with the test engineer and instrumentation technician inside that vehicle.

The testing procedures were essentially the same in all cases after the instrumentation was installed, cables were connected, and the recording system was warmed up. The first stage was initialization of the data acquisition system. Each active data channel was balanced and scaled, so that no load on the bridge resulted in zero output and a full scale calibrate signal, induced electrically by a switch in the multiplex system, resulted in a 500 Hz frequency shift.

After all channels were balanced, each multiplex was monitored for a few vehicle passes to verify reasonable operation of the instruments and data channels of that multiplex. Any non-existent or unreasonable signals were investigated in an orderly and disciplined manner. The first step was to identify whether the problem was inside or outside the Mobile Laboratory. This was done simply by exchanging the cables of the faulty channel with those of a good channel. If the problem was outside, the instrument was first checked, and then the cables and connectors were checked. Faulty instruments or cables were replaced. If the fault was inside, the multiplex signal conditioning cards were checked first, and then the internal patch connectors were checked. Faulty cards were repaired or replaced, and faulty cables were replaced.

At one time or another, problems occurred with accelerometers, displacement transducers, strain gauges, traffic counters, lead cables and connectors, patch cables, signal conditioning modules (including the VCO), discriminators, the oscillograph, and the balancing panel. However, experience from prior use of the equipment and an orderly approach to investigation of problems rarely resulted in a delay of more than half an hour.

At the beginning of a test, the time clock was started and watches were synchronized with it to standardize all time references. A new tape was mounted on the recorder, if necessary, because often a partially-used tape remained from the previous test. When all was ready, the

instrumentation technician informed the job captain. When it was safe, the bridge or bridges (if both members of a twin bridge were being tested) was closed to traffic for about three minutes for a final balance of the multiplex channels and recording of about one minute of zero and one minute of full scale calibration signals set electronically from the control panel on the tape and oscillograph. This calibration was an essential start to the test because without it it would be impossible to establish exact voltage levels for playback of the analogue tape.

At this point the test would be ready to commence. Instrumentation and the data acquisition system would be working. The test vehicles would be parked on the shoulder a short distance from the bridge. Flagmen would be stationed at either approach to the bridge and at any access roads or ramps close to the bridge. An Ontario Provincial Police cruiser would be on-site to assist with traffic control.

The procedure for operation of a single run was as follows.

1/ The trucks would inform the job captain by radio that they and the police cruiser were in position for the next run.

2/ The job captain would call when everything was ready at the test site, confirm the requirements for the next run, and ask the police officer to stop traffic behind the test vehicles.

3/ When a gap appeared in approaching traffic the police officer would activate the flashing red lights of his cruiser and pull out onto the highway.

4/ The test vehicles would then commence the run, proceeding at appropriate speed and spacing, if following each other, or taking any other specified relative position.

5/ The police cruiser would follow at a slow speed keeping traffic behind the test vehicles.

6/ The lead vehicle would call the job captain when the run commenced, and the job captain would then call the flagmen and have them stop traffic approaching the bridge from the opposite direction (for a two-way bridge) or from other ramps.

7/ When the test vehicles were some 20-30 seconds from the bridge, the job captain would call the instrumentation technician to start the tape recorder and inform him of the run number.

8/ The technician would start both the tape recorder and the oscillograph and log the time, lane, travel direction, vehicle, and run number for each run.

9/ The test vehicles would pass the bridge and the police cruiser would slow to a halt just before the bridge, restraining any traffic to permit a free vibration of the bridge.

10/ About twenty seconds after the last test vehicle left the bridge, the job captain would visually signal the police officer and flagmen to open traffic.

11/ The instrumentation technician would then stop the recorders unless any trucks in the restrained traffic were deemed worthy of recording.

12/ The job captain would then call the test vehicles and inform them of the next run.

13/ The test vehicles and the police cruiser would then turn around and proceed to their holding station for the next run.

14/ Sequence 1 through 13 would then be repeated.

This operational procedure for scheduled test runs worked efficiently and well. The traveling public was seldom delayed for more than one or two minutes.

The two key elements in this were the excellent radio communication system and the police assistance. Reliable radio communication with a range of 5-8 km (3-5 mi.) is essential for this type of test. Small hand-held radios with rechargeable batteries were found to have neither the range nor the endurance for this, and anything less than fully reliable communications can lead to unnecessary hazards to the test crew and the travelling public when such a test is conducted without full closure of the highway. The police cruiser is readily identifiable, and its flashing red lights commanded the instant respect of motorists even if there was no evident reason for them to stop. Unfortunately, MTC flagmen did not appear to receive the same respect, so traffic control was a little more worrisome when performed by flagmen alone on the occasions a police cruiser was unavailable. However, the test vehicle operators and flagmen were all sufficiently experienced that potentially hazardous situations were avoided by anticipation and no serious problems occurred. The presence of a police cruiser always gave assurance of respectful behaviour by motorists.

The test vehicles always started with runs at 16 km/h (10 m.p.h.) in each normally-traveled lane and along the right-hand side of the roadway as close to the curb as possible. These runs essentially provided a static calibration of the transducers with the known test vehicle loading. The low speed creates only a small amount of vehicle or bridge vibration which can easily be removed by filtering. A further series of runs at higher speeds followed. Generally, these were 48 km/h (30 m.p.h.), the maximum legal speed limit, and the mean of these two speeds. In these runs, all vehicles made a pass in each lane at the prescribed speeds. For continuous bridges, some runs were usually made with the test vehicles following closely at a distance determined by the length of the bridge spans. For one-way bridges, some runs were made with test vehicles side-by-side and in echelon formation. These two series would also be performed at the three basic speeds as outlined above.

In addition, some of the earlier test runs were made with test vehicles that entered the bridge at about 48 km/h (30 m.p.h) and performed normal braking and slowing for a while, but did not come to a complete stop. The basic run series would be repeated as time permitted.

For lightly travelled bridges, it was considered desirable to obtain eighty or more individual test vehicle passes, whereas for the heavily travelled ones, a lesser number was adequate as heavy commercial traffic could be sampled more readily.

Passes made by heavy commercial vehicles were also recorded. This included most vehicles of three or more axles, and some with two. The Mobile Laboratory was generally parked so that both approaches to the bridge could be seen from some location inside. A remote switch was then used from this location to start and stop the tape recorder. When the approaches could not be seen, either the tape was allowed to run continuously or the job captain called out tape start/stop instructions via the intercom. On bridges where truck traffic was light, all trucks were recorded. When truck traffic was heavy, recording was more selective and preference was given to those which were well-separated from other traffic, or to groups of trucks traveling close together at a reasonable steady speed.

Full attention was given to public safety during the testing of bridges. Flags and warning signs were erected at approaches to the test site, although it was not possible to put advisory signs marked "slow" as this would thwart the test objectives. All activities were conducted where oncoming traffic had adequate sighting distance. Flagmen were stationed so as to be clearly visible to traffic. Test runs were not made while it was raining because of reduced driving visibility and braking capability.

An important part of the test was a subjective evaluation of the vibration response in the bridge due to the passing of heavy commercial vehicles, including test vehicles. A technician, or any other available person, was asked to stand on the bridge beside the accelerometer which was expected to give the largest response, and then to rate the bridge's response. The run was identified by the time of day, any notes, and a rating of between 1 and 6 which was given following the descriptors of Reiher and Meister [7]. On a number of bridges, two or more independent ratings were obtained, whereas on the rest there was only one. The raters generally had worked extensively on bridges, and knew that vibration could be expected. However, in a few instances where less sophisticated raters were used, good agreement was found between the ratings of those accustomed to bridge vibration and those unfamilar with it.

6/ DATA PROCESSING

6.1/ Modal Analysis

Modal analysis was performed using a system based upon a Nicolet Scientific Corporation Model 660A dual-channel fast discrete Fourier Series analyser, and a Model 160C Mass Storage. This equipment was used in conjunction with a Hewlett-Packard 9845T processor, which could control the use of the Fourier analyser, collect the data and format it in final report form on its own printer/plotter and a Hewlett-Packard 9872C plotter. A block diagram of the system is shown in Figure 20, including playback and demodulation of the analogue data, and a view of the system is shown in Figure 21. The system used is primarily for modal analysis of vibration data obtained from accelerometers and is based at the MTC Instrumentation and Testing Laboratory at Downsview.

The analyser has two input channels. In the time domain it can display the time histories of the input channels, their impulse response and auto-correlations, and the cross-correlation between them. In the frequency domain it can display the r.m.s. and power spectra of the two channels, the cross spectrum, transfer function, coherence, transmissibility, and coherent output power between them.

Analysis was designed to produce the frequencies, mode shapes, and damping ratios of the lowest frequency vibration modes of a bridge. The actual modes, and their number, depended upon the degree to which they were excited by passing vehicles. For an N-span bridge, it was often desirable to determine the first two groups of N longitudinal flexural modes, together with the corresponding torsional and transverse flexural modes. For bridges with a fundamental frequency below about 6 Hz, a frequency resolution of 0.1 Hz was considered adequate, whereas for bridges with a fundamental frequency above 6 Hz, 0.2 Hz was considered adequate. Great accuracy was not demanded from the modal analysis, as the limited number of accelerometers, fixed for the duration of the test, did not permit detailed definition of mode shapes. Rather, the intent was simply to characterize the modes. Analysis proceeded in three phases: identification, data acquisition, and extraction of the results.

In the first phase, the data on the tape was previewed for signal levels and events of interest to determine the runs to be used in the analysis and analyser input settings.

Data acquisition, the second phase, proceeded with the tape recorder running at four times acquisition speed, or 762 mm/s (30 in./sec.), and data was filtered in this mode at 200 Hz, equivalent to 50 Hz real time. Sufficient runs were read into the analyser until the peaks of the auto-spectra, averaged over all the runs, were resolved to the desired accuracy. This also averaged away forced vibration of the bridge by vehicles crossing it. One accelerometer was chosen as the reference and always read into analyser Channel A. Data acquisition was triggered from this channel. The same runs were read with the reference accelerometer always on Channel A and each of the other accelerometers, in turn, on Channel B. The transfer function between Channels B and A identifies the system having Channel B as output and Channel A as input, and defines the amplitudes and phases of other accelerometers relative to the reference accelerometer at all frequencies. At the modal frequencies, the transfer function represents the mode shapes.

The coherence between Channels A and B was also computed. This is a measure of the repeatability of the transfer function between the signals on Channel A and Channel B. There are fixed amplitude and phase relationships between all points on a bridge when it vibrates in one of its modes. The coherence is, therefore, expected to be over 0.9 at frequencies of modes of the bridge, and low at other frequencies. When two peaks occur close together, coherence is the best means to determine if one or both is a mode of the bridge. All data was checked for validity during acquisition and then stored in a file on the floppy disc at the Nicolet 660A for subsequent use.

Runs having a well-defined residual vibration after a vehicle had left the bridge were also identified in the first phase. As a part of the second phase, the acceleration time histories of these runs were also stored on floppy disc for later determination of damping ratios. Where several modes, particularly flexural and torsional modes, had frequencies close to the mode of interest, a composite signal was obtained as a linear combination of a subset of the acceleration time histories of a

run. The sign of each signal was chosen to suppress modes other than that being processed, and particularly the beating that occurs between modes. Each composite time history was then filtered using a narrow bandpass filter centred on the frequency of a mode. Its damping ratio was computed by the Hewlett-Packard 9845T using an average logarithmic decrement. Several runs were processed in this way for each mode so that average values for damping ratio could be obtained.

In the final phase, the stored data, consisting of auto spectra, cross spectra and time histories of free vibration decays were recalled from their files on floppy disk. This data then was transmitted to the Hewlett-Packard 9845T processor, formatted and plotted as auto spectra, transfer function, coherence, mode shape, or time history on the Hewlett-Packard 9872C plotter, or listed on the internal printer/plotter of the processor.

6.2/ Digitization

Digitization of data captured in the field was performed using a Data Transcription System, based upon a mini-computer, in the MTC Testing and Instrumentation Laboratory. The digital data was stored on an IBM-compatible magnetic tape for further processing. The Data Transcription System is shown in Figure 22, and a schematic of it is shown in Figure 23.

The test engineer selected time segments of interest for further processing from the oscillograph records made during the test. The start time was chosen at least two seconds before the truck entered the bridge. This leader was necessary to permit data channels to be zeroed, as described in the next section. A longer leader would be necessary if the traffic detectors were much before the bridge, or if other traffic immediately preceded the truck onto the bridge. The stop time was also at least two seconds after the truck left the bridge, and permitted some decay of free vibration. When more than one truck followed another closely, such that the above requirements could not be met for each, the time segment selected included several truck passes. Time segments were also chosen wherever possible in standard lengths of 10, 15, 20 or more seconds, as appropriate for the run.

The start and stop time codes were supplied to the laboratory technicians, who punched them onto a paper tape. The tape was read by the ASR33 Teletype and stored in the F8 micro-computer, which was programmed to compare the time code coming from the FM tape with the stored start/stop times, to check them, and to initiate or terminate digitization activity by the PDP-8A mini-computer.

The first stage was simply a check to verify that the time codes selected were on the FM tape. Sometimes a stop code was selected from an oscillograph record that was left to run after the tape was stopped during the test. The tape was simply left to run under control of the F8 micro-computer and it stopped when an invalid time code was encountered. This was then corrected from the CRT keyboard and the tape was restarted. When the time codes were correct, they were re-punched on paper tape for later use.

Digitization was done for each track of recorded data. All runs on the first track were digitized first, followed by all runs on the second track and then the third track. Use of the time code, which was read directly from the tape, and tape speed compensation, ensured precise synchronization of data for all three tracks. When a track was selected, the full scale calibration put on the tape before or during the test was used to set the discriminators to exactly 2.0 V output. The 12-bit analogue to digital converter was set to 2.5 V, so that full scale at the recording stage was represented by approximately 1638 counts [i.e., 2047 x (2.0/2.5), at the digitization stage]. Thus, a displacement transducer with a sensitivity of 0.063 mv/V/mm (1.6 mV/V/in.) had a full scale of 15.875 mm (0.625 in.) The digital data had a resolution of about 0.001 mm (0.0004 in.), which is less than the nominal resolution of the instrument. Setting of the discriminators at 2.0 V permitted a 20% over-range capability of the multiplex system to be used without saturation of the analogue to digital converter.

When the discriminators were set up, the paper tape of start/stop times was read into the F8 micro-computer. The magnetic tape was then started, and played back at 762 mm/s (30 in./sec.), or four times the recording speed, in order to reduce the time for digitization from about 90 to 20-25 minutes per track. Data from all channels was filtered at 200 Hz,

equivalent to 50 Hz in real time. Digitization was performed by a program running on the PDP/8A computer under control of the F8 at a rate of 400 scans per channel per second, equivalent to 100 scans per channel per second in real time. Digital data was written, in fixed length blocks of 512 8-bit bytes, onto an 800 b.p.i. IBM-compatible magnetic tape. Each block had eight bytes of identification at its head followed by 252 16-bit (two byte halfword integer) binary data values.

After the first track was completed, an end-of-file mark was placed on the digital tape. The FM tape was rewound and the second and third tracks were digitized following the same procedure. An end-of-information mark was placed at the end of the digital tape. The digital tape was rewound and verified by reading every block of data. If errors were found, the digitization process was repeated with a new tape. When a tape was satisfactory it was forwarded to the test engineer for further processing.

6.3/ Digital Data Processing

The digital data were processed on the IBM 3033 computer available to MTC. A schematic of the analysis system is shown in Figure 24.

Analysis proceeded in three steps. The first step in the analysis was to sort and scan the 800 bpi digital data tape produced by the Testing and Instrumentation Laboratory onto a 6250 bpi MTC library tape, with multiple records per block for more efficient processing. The sorting was accomplished by a small special purpose program. The raw data tape contained all runs from one track on the FM tape, chronologically in a single file. Thus, when three tracks of data were recorded, there were three files on this tape. The sorting program re-arranged the data so that all channels for one run were together, with all runs chronologically in a single file of the output tape. The data were also scanned during sorting to ensure that data ranges appeared reasonable.

The second step used the general purpose data analysis program TEDANA. This program read the raw data from tape, and stored them on disc in a standard format for access by various standard processing operations,

such as for calibration, filtering, detrending, statistics, and plotting. A special purpose subroutine was written to interface with TEDANA which scanned a run to produce:

- maximum positive and negative static responses;
- maximum positive and negative dynamic responses;
- maximum free vibration response;
- maximum acceleration;
- vehicle speed and lane of travel; and
- storage of the scan results in a dataset on disk.

This subroutine was tested on typical runs for various bridges before the bulk data were processed. All changes, whether for correction of an error or enhancement of performance, were checked by repeated runs until the results were deemed satisfactory.

In the final step, the scan results stored on disk were processed by a small special purpose program to produce formatted tables for inclusion in the test report. These tables included:

- a run log;
- a table of truck distribution by type and weight;
- static and dynamic responses of each instrument by run;
- dynamic amplifications by run;
- acceleration levels by run;
- statistical summaries of dynamic amplification as a function of various parameters; and
- statistical summaries of dynamic loads, truck weight x dynamic amplification.

This data processing was quite straightforward in principle, but in practice it was rather complicated, for three reasons. The first was simply the bulk of the data, and the number of interacting datasets necessary to conduct the analysis. The second was the nature of the data, whereby every run had to be given individual attention to ensure that it was correctly processed in spite of interferences or anomalies. The final reason was bridge configuration, which made it impossible to standardize the scan procedure for all bridge types and instrumentation patterns. On-line procedures were developed to eliminate redundant operations and

automate data preparation and submission of computer runs. These reduced work and potential for error, and so provided some quality assurance. All input data and results were carefully checked, and where anomalies or interference could not be resolved, the results were not included in final statistical summaries.

It is a shortcoming of much of the published work on dynamic testing of bridges that the data analysis procedure is not well described. This inhibits judgement of the work, and so may limit the usefulness of the results published. The bridges tested in this work were instrumented fully across one or more transverse sections. This, and the volume of data, resulted in development of a rather comprehensive semi-automated data analysis procedure. This procedure, comprising the final two steps outlined above in general terms, will now be described in more detail.

For the purpose of this description, four definitions of response of an instrument to a truck pass are necessary, as illustrated in Figure 25. The dynamic response is the measured response. The static response is that response which would be measured if, by some means, the truck and the bridge could be totally inhibited from vibrating; it is approached in form, though stretched in time, as truck speed is reduced to a crawl. The dynamic component of response is the algebraic difference between the dynamic response and static response. The dynamic amplification is the ratio of peak dynamic response to peak static response, minus unity. This latter definition is made quite generally here, and will be refined subsequently so that test results can be compared with code provisions. Notice that the peak amplitudes of dynamic response, static response and dynamic component do not necessarily occur at the same time.

The data tape consisted of a calibration segment of zero and full scale signals, and a number of data segments. Each data segment contained one or more events. An event is either a pass by a single truck, a pass by more than one truck in such a way that each pass is individually distinguishable with no significant interference of static responses between trucks, or a pass with two or more trucks simultaneously on the bridge and significant interference between their static responses. The key to successful automated data analysis was identification of the time for which each truck, or the trucks of a simultaneous presence event, was

on each span of the bridge. This task was complicated not only by multiple events within a single data segment, but also by interferences from light trucks and other vehicles not of interest but which nevertheless caused small static responses of the bridge during a data segment.

Input data were required to control processing of each segment of the data tape. The sequence number in the file, the run name, start and stop times, and the segment type, either calibration or data, were supplied. For each data segment, the number of events and information to assist with zeroing were supplied. For each event, the run type, either test vehicle or traffic, lane of travel, nominal speed of a test run, and start and stop times with the data segment of the event on the first span of the bridge, were supplied.

The autoset zero and full scale calibrations recorded at the start of every test and FM tape were used to set up the discriminators for data playback. A short segment of this calibration was also digitized. The mean span, equal to the difference between mean full scale and mean zero, was computed and used as a correction to the nominal instrument sensitivity. The correction was generally much less than 1% percent of full scale, because the discriminators were set with care. The corrected instrument calibrations were stored for later use when each run was processed.

During the course of a test, the initial zero of electronic displacement transducers or strain gauges would change somewhat due to the movement of the sun changing the thermal loading of the structure, electronic drift and, possibly, other factors. The response of each instrument for each data segment was therefore zeroed before any processing was conducted. In normal cases, the average of the first two seconds and the last two seconds of the dynamic responses were computed separately. In cases where other interferences were present, initial and final averages of different duration and starting point were computed according to data supplied. If the initial and final averages differed by more than 4% of full scale, the instrument response was rejected for that data segment. Otherwise, the initial average value was subtracted from every data value in the entire record to zero it. The initial average value of every instrument was printed for each run to provide a record of drift during

the test. Any value which was significantly out of the long-term trend rendered that instrument suspect, and it was examined either for re-processing or for rejection from final statistical analysis.

The dynamic response of an instrument consists of the static response plus the dynamic component. The latter can be supressed by passing the dynamic response through an appropriate linear phase lowpass digital filter. Using a standard program [8, 9], a filter was designed for each bridge having a passband with maximum deviation less than 0.5% of full scale to a frequency greater than V/L Hz, where V is the maxium speed in m/s, and L is the shortest span in m, and a stopband with cut-off below the first bridge vibration mode frequency and a maximum deviation of about 1% of full scale. The number of filter weights required varied between about 100 and 200, depending upon the actual parameters selected, the passband and stopband deviations, and the width of the transition band. The zero leader provided at the beginning and end of each data segment was sufficient to avoid any transient effects with the filter -- if the data had not been zeroed, the non-zero leader would have resulted in the filter step response being seen at the start of the filtered record. For a given bridge, initial filter parameters were selected and tests were made on typical runs. The results were evaluated by output from the filter routine, and by inspection of CALCOMP plots of dynamic and static responses. Parameters were varied until an economical filter was found that gave satisfactory static responses. This produced good results for bridges with spans greater than about 20 m, but was questionable for spans around 15 m and definitely unsatisfactory for the 5 m spans of the three timber bridges tested [4, 6]. The process of zeroing and filtering is shown in Figure 26.

Instruments were generally placed within a span at the locations where largest static response was expected. Typical static and dynamic responses for instruments at the middle of the centre and end spans of a three-span continuous bridge are shown in Figure 27. Three response regions called positive, negative and residual are defined in the figure for either instrument location. The positive region is when the truck is on the span containing the instrument. The negative region is when the truck is on a span adjacent to that containing the instrument. The residual region is when the truck has left the bridge, and the bridge is in

free vibration. Instruments on a simple span have no negative region. Instruments on an end span of a continuous bridge have one negative region, either before or after the positive region, depending upon whether the span is the last or the first encountered. Instruments on an interior span of a continuous bridge have two negative regions, one before and one after the positive region. The peak values shown in Figure 27 were the desired results for every instrument for each event. The values are defined as:

DPR = dynamic response, positive region
SPR = static response, positive region
DNB = dynamic response, negative region, before vehicle reached span containing transducer
SNB = static response, negative region, before vehicle reached span containing transducer
DNA = dynamic response, negative region, after vehicle left span containing transducer
SNA = static response, negative region, after vehicle left span containing transducer
RES = dynamic response, residual region

The terminology of positive and negative regions was chosen for the general case when presence of a truck on a span would produce a positive static response from an instrument on that span, and a negative static response from an instrument on an adjacent span. When the members of a truss were instrumented with strain gauges, tensile strains did not necessarily correspond to truck position on the span containing the gauge, so the signs of calibrations were changed as necessary to ensure conformity with this convention. When a strain gauge was placed close to an internal support of a continuous bridge, the response was usually one positive region while the truck was on the two spans adjacent to the support. This case was treated separately.

Highways in Ontario are designated as east-west or north-south. For each case, the nominal direction of travel for a two-way highway was either eastbound or northbound, and the alternate was, of course, either westbound or southbound. Key instruments were designated for each normal traffic lane for each span from which occupancy times would be determined for each truck. An alternate was also designated, to be used if the

primary key instruments were unable to provide these times. An example plan of instrumentation, for a two-span continuous bridge, is shown in Figure 28. Key instruments for the eastbound lane are 4 and 9, and for the westbound lane, 2 and 7 for the west and east spans, respectively. Alternates are 3 and 8 for the west and east spans. The direction, and hence lane, of travel of each single truck event was known from data. The static response of each key instrument for the specified lane of travel was used in an attempt to find the times of occupancy of each span by the truck. Details of this procedure are given below. If the instrument response was "bad", or the truck was not found, the key instrument for the other lane would be tried, and finally if that failed the alternate key instrument would be tried. If no truck was found, the data segment was rejected. If it was accepted after some failures, the results were carefully inspected to see if the results were meaningful or should be rejected.

Occupancy times for a truck on each span of the bridge were obtained by examining the static response of each key instrument. For the standard case shown in Figure 29, a tolerance was established at a level greater than the typical static response of cars, recreational vehicles or light trucks, but less than that expected from heavy trucks of 100 kN or more. This tolerance was usually about 4% of full scale, about 0.6 mm for a displacement transducer or 10 micro-strain for a strain gauge. The intersection of the tolerance with the static response of each key instrument provided the occupancy times (t_1, t_2) for span one and (t_3, t_4) for span two, as shown in Figure 29. Since the truck had finite length, and the tolerance was finite, t_3 was always greater than t_2 when the spans were equal to or greater than the length of the truck. A more accurate time for the transition of response was obtained by setting $t_2' = t_3' = (t_2 + t_3)/2$. For short continuous spans, when t_2 would be greater than t_3, this averaging was not done.

Where there were multiple events on a single span, the input data defined the event boundaries within the data record, and on-off times were established for each event simply by searching only within the prescribed boundaries and not over the entire record.

Difficulties arose with bridges of three or more spans because a low positive response could arise due to a truck two spans removed from that

that containing the key instrument. For a single truck on such a bridge, the on-off times would be established for the first span encountered, and the peak response would be found. A second tolerance, 60% of the peak response would be set, and the times at which the second span key instrument response crossed this tolerance would be found. The time difference then is assumed to be the time to travel from span to span, and was used as a starting point to search backward and forward for the on- and off-times, respectively, for that span. The same technique was then repeated, with data from the (n - 1)'th span being used to find the on-off times for the n'th span. This technique worked well for the bridges tested, which had span ratios greater than 0.4. Again, the off- and on-times for adjacent spans were averaged to obtain a true transition of response.

The case of multiple events on a multi-span continuous bridge was handled by using data to specify boundaries for each event on the first span encountered. The technique described above was then used for each event separately. When all trucks were travelling in the same direction, there was generally no confusion as typical headways would not result in trucks having a clear separation less than two span lengths, so there would be little static interference between following trucks. When the trucks travelled in opposite directions, there would usually be at least three spans whose static responses would be affected by the passing of each pair of trucks.

For short spans, where the vehicle length is close to or larger than the span, the tractor and each axle group would result in a peak of the key transducer response, as shown in Figure 30. Of the two cases shown in that figure, the first gave the correct on-off times, but the second did not. For this case all peaks within a time interval consistent with vehicle length and speed, and span length, were taken together to establish the span occupancy times.

Once the on-off times had been established for each event on each span of the bridge, it was straightforward to scan to obtain the responses of interest. Because filtering was rather costly, a time segment of interest was established from the start of data or two seconds before the on-time of the first event, to the earliest of end of data or four seconds

after the off-time of the last event. The response of each transducer was then filtered, excepting those key transducers which had already been filtered during the scanning for on-off times. The seven peak response values shown in Figure 27 were then found for each instrument by scanning its response within the times the truck was on the span containing the transducer or on adjacent spans.

Accelerometer responses were scanned during the time each truck was on the span containing the accelerometer. During this time, the peak positive acceleration, peak negative acceleration, and peak 1.5 second moving root-mean-square acceleration were found.

The results of these scans for each event were printed, and also stored in a dataset on disk for subsequent analysis.

It was found to be highly desirable to process data from all runs on one digital tape file in one computer run, to simplify subsequent processing by the statistical summary program. To do this, it would be necessary to have no data errors or anomalies in the entire tape file and other data files. This ideal was unachieveable. The special purpose data processing subroutine coded for TEDANA was therefore made tolerant of as many errors as possible, and was made able to detect anomalies in the data. This meant the run could proceed to completion or until a truly fatal error was encountered. When an anomaly was detected, that data channel was marked "bad" for that data segment. If too many data channels were marked "bad" on one run, or some other irrecoverable error was encountered in the data, the entire run was marked "bad". These marks were stored on disk with the peak value scan results, for use by the subsequent statistical program. If only a few channels or data segments were found "bad", the computer run was accepted as satisfactory. However, if a similar pattern of "bad" marks persisted over a large proportion of data segments, it would be investigated, the problem would be resolved, and the job re-run.

The work involved processing a large volume of data, which was expected to be potentially rather costly of computer resources. Considerable efforts were made to be economical in the use of these resources by design of the special purpose data processing subroutine for the program

TEDANA, and use of standard operations. Processing of data segments was scheduled to minimise input and output operations with bulk working storage on disk, and especially to minimise the very costly digital filtering. The key transducers used in defining the occupancy times of a truck on a span were processed first and had, of necessity, to be filtered in their entirety before they could be scanned to determine occupancy times. The filtered data records were saved on disk, to be recalled later for peak value scanning. Once occupancy times were established, other data channels were only filtered for the duration of the truck on the bridge.

The data from a particular test would consist, in general, of several files on a library tape volume. Each file corresponded to an FM tape, or part thereof, and was processed in a single computer run as described above. This resulted in one dataset of scan results on disk for each data file on tape. The results for a bridge were generated by a short specialized program which produced summary lists and statistics in tabular form for inclusion in the test reports [4, 6]. The scan results datasets were concatenated as input to this program, and a small amount of additional input was required to control the processing. The program also had options to exclude from processing single events, a sequence of events, or individual instruments for a single event or sequence of events.

The summary program produced a run log; a table showing the distribution of trucks by type and weight, where numbers warranted and weights could be estimated accurately; a listing of peak acceleration levels by run; a listing of peak static and dynamic responses for positive, negative and residual regions by run; and a listing of static responses for each calibration run.

The calibration runs made in the normal traffic lanes by the Test Vehicles permitted instrument peak static responses to be developed as a function of truck weight, as shown in Figure 31 for one of the lanes of an example bridge with four instruments at the middle of a span. When a truck of unknown weight crossed the bridge, the peak static response for each instrument was interpolated conceptually in the chart like Figure 31 for its lane of travel, and an estimate of weight was obtained

by averaging the interpolated weights for all instruments. Care was taken to include in this process only instruments which appeared to be functioning correctly. This procedure generally worked very well for spans greater than 30 m, and became progressively less accurate as spans decreased towards the length of the vehicle. It was not useful at all for spans less than 20 m, where some technique which deals with axle groups should be used. However, since weighing vehicles was not a primary objective of the work, no effort was devoted to developing a procedure for weight estimation on short-span bridges. The simple weight estimation procedure outlined here resulted in estimates of Test Vehicle weights generally with a coefficient of variation much less than 0.05 for bridges with spans greater than 30 m and runs made at speeds from 48 to 97 km/h. TV2 generally had the largest variation, possibly because of less accurate lane tracking by its driver than for the other Test Vehicles.

The traffic detector signals potentially contained information to confirm truck lane of travel, and to provide truck speed and number of axles. The pressure switches did not always function reliably, as spurious pulses sometimes occurred and expected pulses sometimes did not occur. Since the information they could provide was secondary, no effort was expended to deal with the signals in a comprehensive manner. Speed was deduced from the time interval between the first positive and first negative pulses and the spacing between the pressure tubes. If an unreasonable value resulted, it was ignored. This simple approach worked well, as expected, for Test Vehicles when no other vehicle was on the bridge. It was less reliable for trucks passing in traffic due to the presence of cars in the traffic flow. However, since free flowing traffic in a rural area usually travels close to the speed limit, little error was expected in truck speeds if it was actually derived from a preceding car.

Instruments were located in one or more lines transversely across each bridge. Dynamic amplifications were computed for each response region for each line of instruments for each single vehicle event. In any instrument line, the data channel having the greatest static response SPX served as the reference. Dynamic amplifications were computed for this channel, for all other data channels having static response within 10% of SPX, and for all data channels having dynamic response greater than the dynamic response of the reference channel.

Dynamic amplifications were computed for each qualifying data channel as:

- DA = (DPR-SPR)/SPX -- for the positive region;
- DA = Max(DNB-SNB,DNA-SNA)/SPX -- for the negative region; and
- DA = RES/SPX -- for the residual region;

where the quantities are defined in Figure 27. The dynamic amplifications for all qualifying data channels are relative to the largest positive region static response. Dynamic amplifications in the three regions may, therefore, be directly compared. This procedure ensures a dynamic amplification is not over-estimated, as it would be if computed from the static and total responses of a non-critical data channel.

Figure 32 shows an example of over-estimation of dynamic amplification if static and dynamic data from Girder 1 alone, or Girder 2 alone, would be used. In this example, using the above description, Girders 3 and 4 would be qualifying data channels and the dynamic amplification for both would be relative to the static response of Girder 3. This process may appear illogical, as it relates the dynamic response of one instrument to the static response of another. However, it does ensure that the largest observed dynamic response is related to the largest observed static response. This is demanded when dynamic load is modelled proportional to static load, as in current design codes. A listing of dynamic amplifications was presented by run. This process often resulted in more than one dynamic amplification being computed for each transducer line.

Multi-vehicle events which resulted in more than one vehicle simultaneously on a span were rather infrequent, except where they were part of a scheduled test run for a bridge on a two-lane, one-way highway. There was no convenient way to compute dynamic amplifications for such events from traffic, because the individual truck peak static responses could not be separated. For two-truck runs by Test Vehicles, where the trucks were in prescribed positions, the calibration runs were used for peak static responses and dynamic amplifications were computed manually for each vehicle separately by taking the dynamic component for a transducer with the governing static response.

The mean value and coefficient of variation (standard deviation/mean) statistics were computed overall for all single vehicle events, both

truck traffic and Test Vehicles, at all speeds in all traffic lanes, for each transducer line and response region. Statistical subsets were also computed for Test Vehicles only by Test Vehicle, lane of travel and speed, and for truck traffic (where numbers warranted) by weight and lane of travel. Where truck weights were reliably estimated, similar statistics were also computed for dynamic load, defined as the product of dynamic amplification and truck weight. Finally, distributions of dynamic amplification were computed for each response region in intervals of 0.025, by percentage of samples within the interval and percentage of samples exceeding the lower boundary of the interval.

7/ DISCUSSION AND CONCLUSIONS

Dynamic tests were performed on 26 bridges in Ontario between August 6 and November 5, 1980. This three-month period included three weeks when the Mobile Laboratory was assigned to other activities. No weekends were worked, although some overtime was required to maintain schedule. The entire test program was completed at a rate of almost three bridges per week, including travel time to and from the sites, which was according to the schedule drawn up at the start of the program. Major factors contributing to the success of the test program within this demanding schedule were the availability of technicians experienced in bridge testing, equipment proven by many years of field use, and the absence of inclement weather. It was found necessary to halt only two tests for no longer than twenty minutes due to rain showers, and weather had no effect on instrumentation activity.

All instrumentation, data acquisition, and data processing systems worked well. No recurrent problems were encountered with any specific piece of equipment.

The relatively small displacements and vibrations of the smaller, stiff bridges taxed the resolution of the displacement transducers. An LVDT of sufficient stroke could be an excellent, but costly, replacement for the strain gauge type displacement transducer used in these tests, both in terms of noise level and resolution.

The traffic detector was based on a pneumatic switch activated by the pressure change occurring in a tube compressed by a wheel passing over it. The switches were susceptible to malfunction from contamination by dirt and dust, but once cleaned and adjusted they generally functioned adequately for the duration of a test. The pulse duration was too short for reliable pulse detection at a digitization rate of 100 Hz, so it was necessary to build electronic "pulse stretchers" to avoid a higher digitization rate.

Digitization and the first stage of data processing, filtering and scan for peak values, were very time-consuming and provided opportunities for error. If a computer-based digital data acquisition system had been available, several months of elapsed time for data processing, and corresponding manpower expenditure, would have been saved. Such a system, programmed to store digital data as a backup, and to scan for and store the required peak values, would have permitted complete on-site analysis of the data.

The test procedure evolved from earlier static and dynamic tests conducted by MTC. It rapidly became standardized, and worked very well. While operations at the test site may have appeared disorganized to visitors, all participants knew their tasks and proceeded to do them with minimal supervision. A number of tests were conducted within a single working day, and the longest required site occupancy for only about fifty hours. The tests were conducted with due attention to safety and no perceived or actual hazards to test crew or public occurred. The principal factors in this were that all members of the test crew knew their tasks; that a reliable radio communication system was maintained; and that the Ontario Provincial Police provided traffic control services. Lack of any one of these elements could have led to the uncertainty which often precedes a hazardous condition.

The test procedure was straightforward and yielded the data required with the least effort and interruption to the highway users. Test vehicles of various configurations were necessary in order to calibrate the bridge by means of slow run in each traffic lane and along the curb. Use of the same test vehicles for all bridges was necessary in order to have a standard basis for comparison between bridges. Simply driving the test vehicles across the bridges was representative of its normal use, and anything else would have been misleading for Code purposes. Again, the use of multiple runs by the test vehicles allowed a calibration against traffic at each bridge and further comparison between bridges. The collection of an adequate sample of bridge responses to heavy commercial vehicles was considered very important because of the multiplicity of vehicle types in Ontario. The Code is a "limit states" code and the statistics of responses to traffic are fundamental in calibration for load factors.

A standardized method of capture of the analogue FM data was essential to efficient modal analysis, digitization, and digital processing. The data collected was voluminous. An average of 100 vehicle passes over each of the 26 bridges, for up to 24 data channels, each sampled at 100 scans per second for 10-15 seconds on average, resulted in something over 80 million words of data. This amount of data could only have been processed by computer. This processing, allied with careful validity checks, was consistent and reliable.

The decision in favour of computer processing was abundantly justified, but a necessary adjunct to this was design of the test to simplify that analysis. In practice it is far easier to test, despite the difficulties of field work, than to perform the data analysis. Further, the time required for proper analysis and reporting can often greatly exceed that required for testing, and this time is often not properly allocated before the test, nor properly protected afterwards. Therefore, if tests are to realize their full value through publication of findings, efforts must be made to simplify and condense the data analysis. It was found necessary to make small compromises in the field portion of the test, which did not penalize the test in any way, but simply imposed the orderly and disciplined test sequence and data acquisition procedure necessary to simplify the analysis.

ACKNOWLEDGEMENTS

This test program was initiated by Paul F. Csagoly, formerly Head of Structural Research at MTC and Chairman of the Ontario Highway Bridge Design Code Development Committee. The job captain was Zdislaw Knobel of the MTC Structural Research Group. Instrumentation and data acquisition was by Bill Stephenson, Bill Kwok, Gary Giles, and Terry Hoshowsky; data digitization was by James Chu; and modal analysis was by Jan Tiessinga and Howard Sahsuvaroglu -- all of MTC's Testing and Instrumentation Research Laboratory. The credit for successful completion of the test program on schedule belongs to all of these, the Inspector 50 crew, Test Vehicle operators, MTC District staff, the various Ontario Provincial Police detachments, and others, and is gratefully acknowledged.

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Volume 2 - Little Rouge Creek Bridge
Volume 3 - Black River South Bridge, Highway 48
Volume 4 - Jock River Bridge
Volume 5 - South Nation River Bridge (WBL)
Volume 6 - Innisville Bridge
Volume 7 - Black River Bridge, Highway 7
Volume 8 - Millhaven Creek Bridge (EBL)
Volume 9 - Millhaven Creek Bridge (WBL)
Volume 10 - Palace Road Bridge (EBL)
Volume 11 - Palace Road Bridge (WBL)
Volume 12 - Eagleson's Road Bridge
Volume 13 - Baxter Creek Bridge
Volume 14 - Cavanville Creek Bridge
Volume 15 - Pefferlaw Brook Bridge
Volume 16 - South Muskoka River Bridge (NBL)
Volume 17 - South Muskoka River Bridge (SBL)
Volume 18 - Gull Lake Bridge (NBL)
Volume 19 - Gull Lake Bridge (SBL)

Volume 20 - North Muskoka River Bridge (NBL)
Volume 21 - North Muskoka River Bridge (SBL)
Volume 22 - Haultain's Bridge
Volume 23 - Townline Road Overpass
Volume 24 - Bostwick Road Overpass
Volume 25 - Black River North Bridge, Highway 48
Volume 26 - Mississippi River Bridge",

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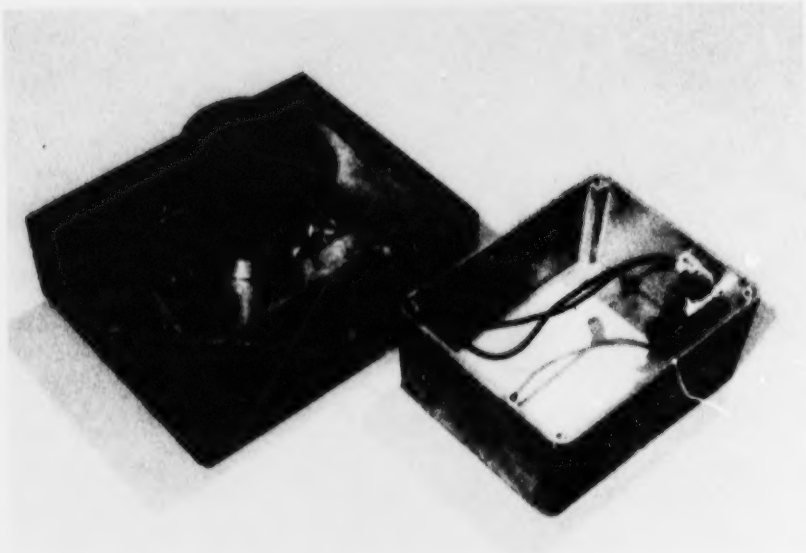


Figure 1/ Accelerometer

Figure 2/ Accelerometer in Place

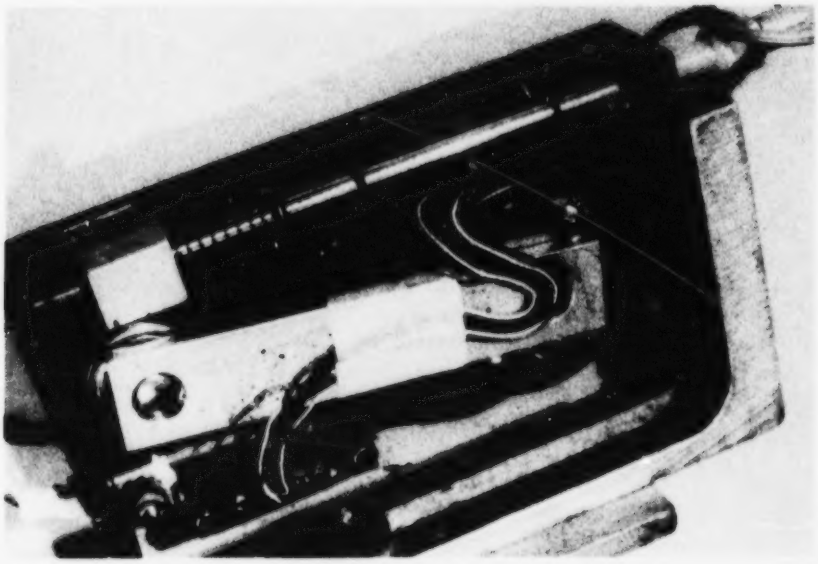


Figure 3/ Electronic Displacement Transducer

Figure 4/ Electronic Displacement Transducers in Place

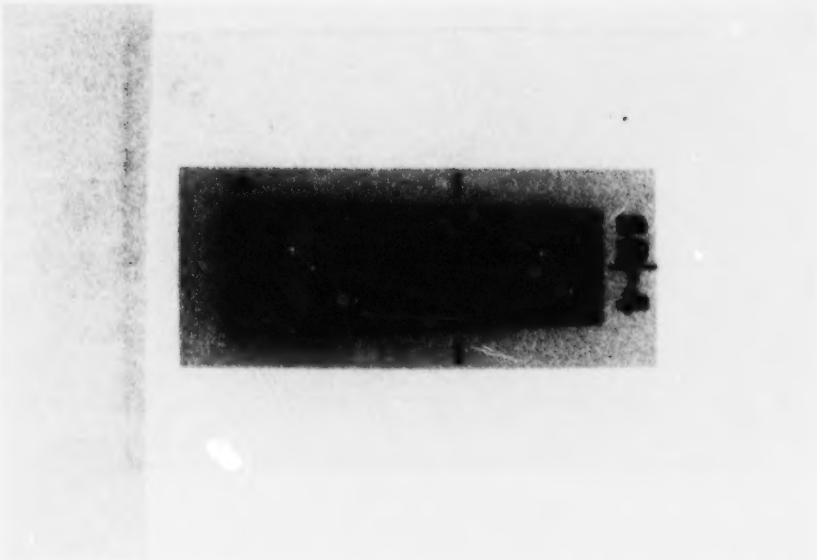


Figure 5/ Strain Gauge

Figure 6/ Traffic Detectors in Place

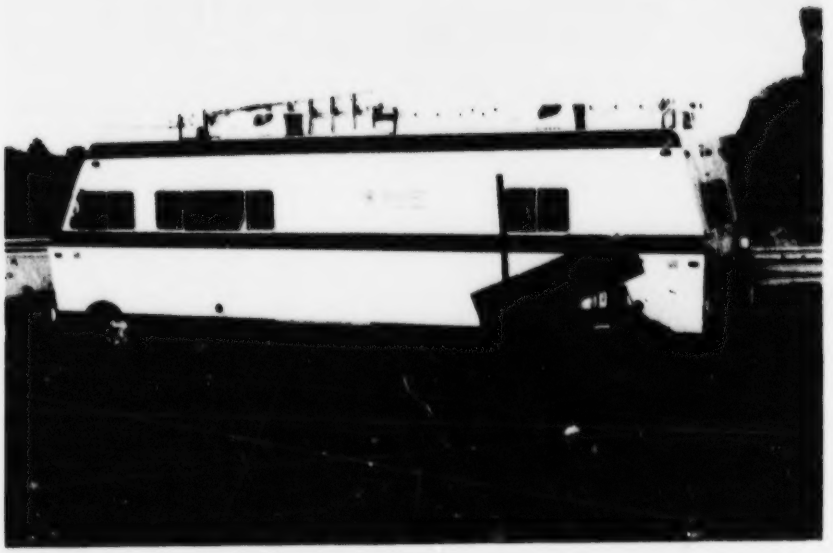


Figure 7/ Mobile Laboratory

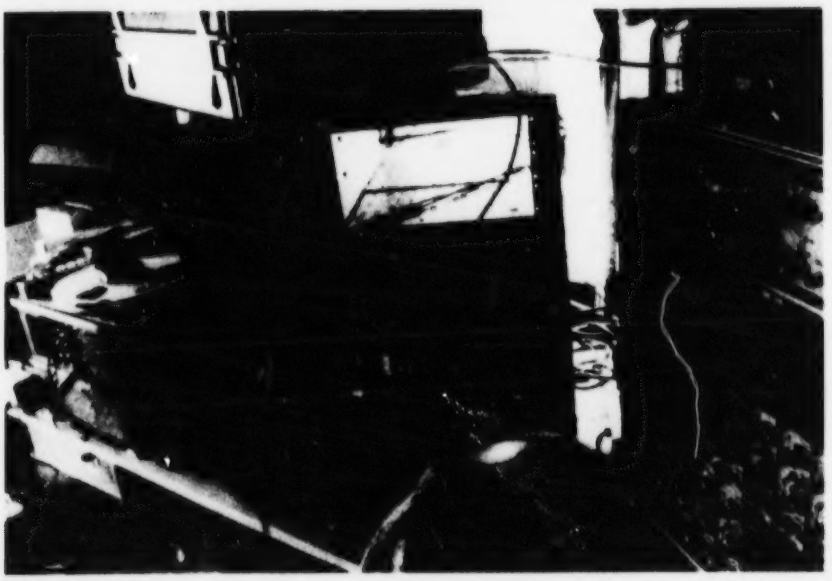


Figure 8/ Data Acquisition System

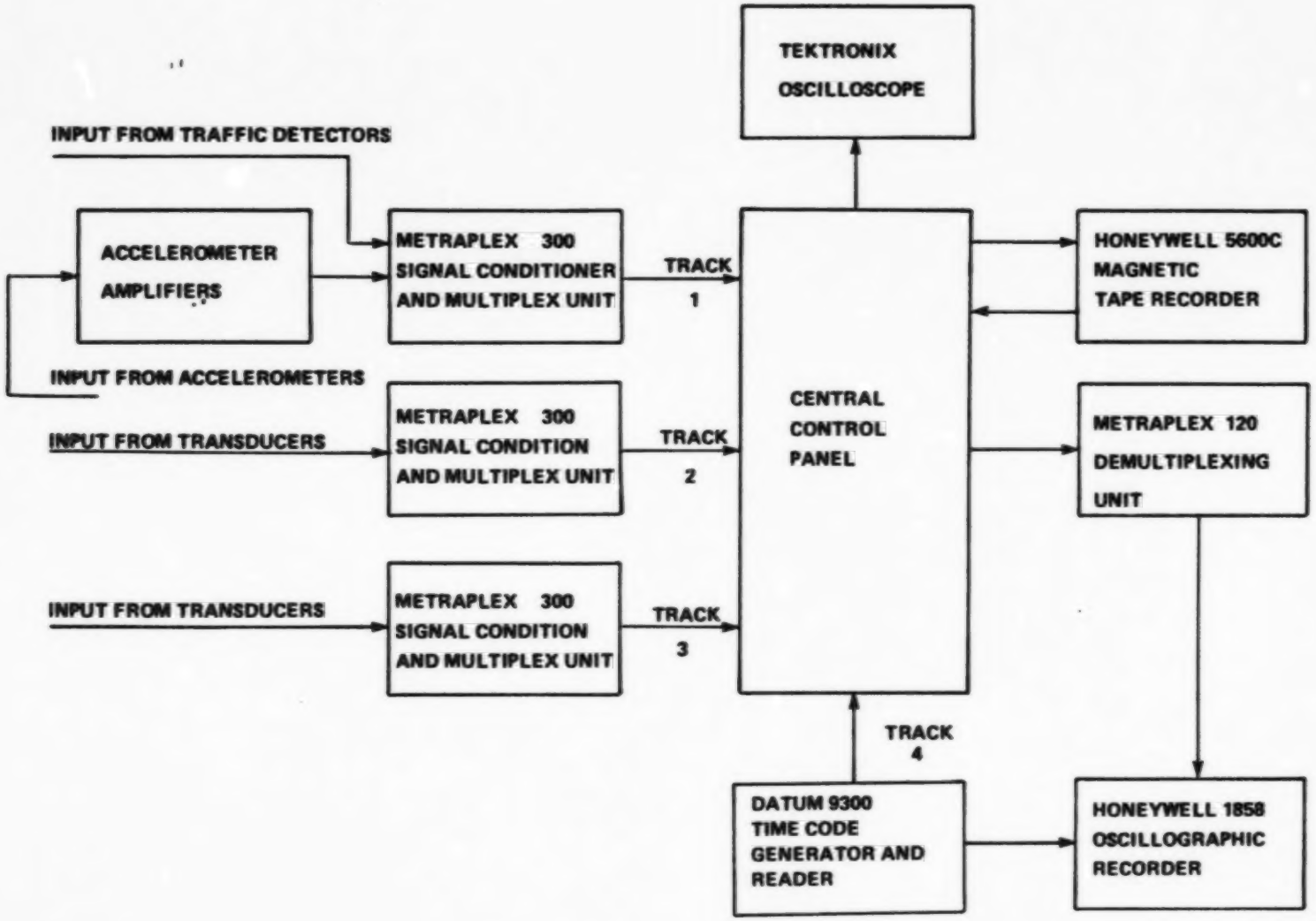


Figure 9/ Schematic of Data Acquisition System

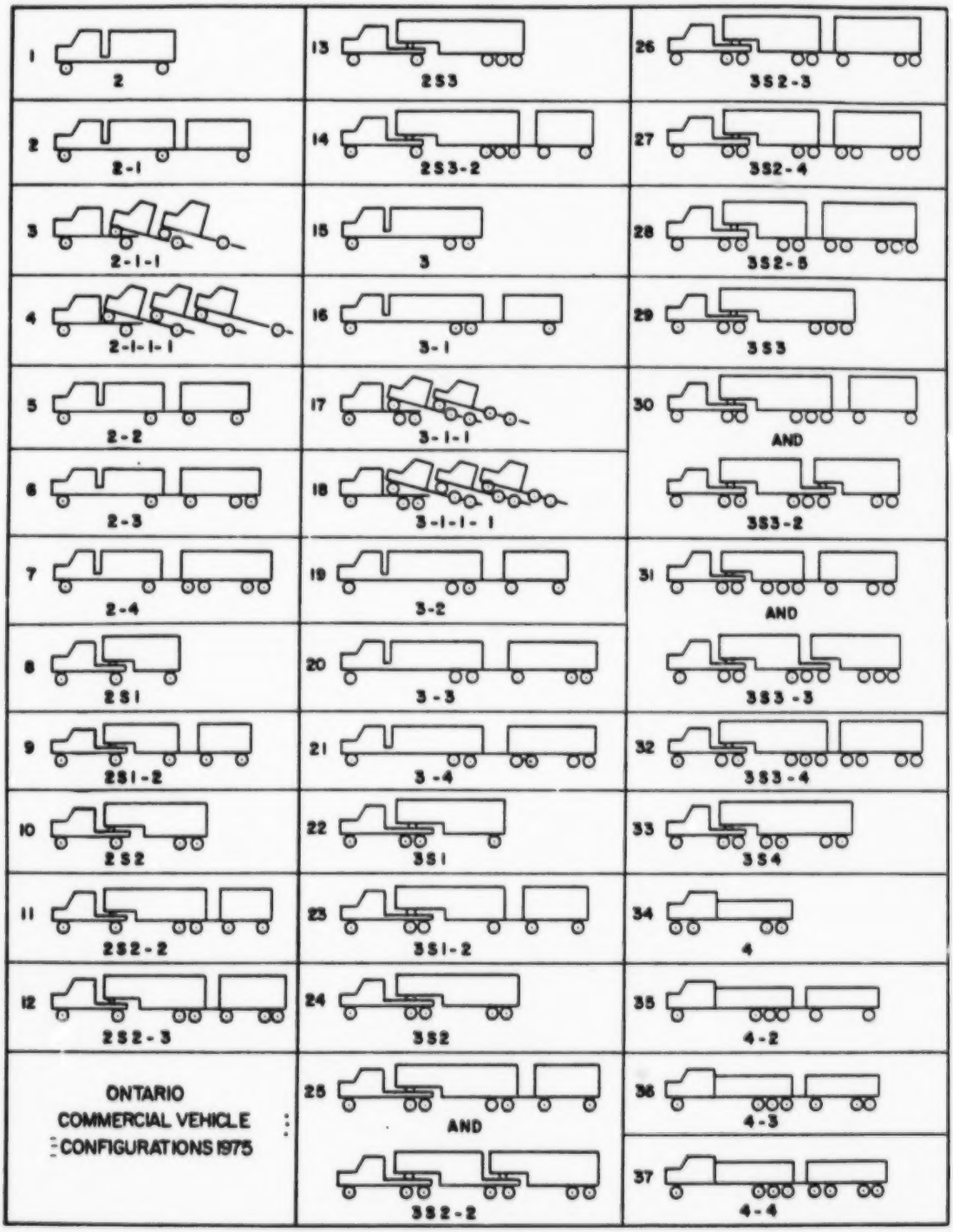


Figure 10/ Classification of Commercial Vehicle Configurations

Figure 11/ Test Vehicle TVI

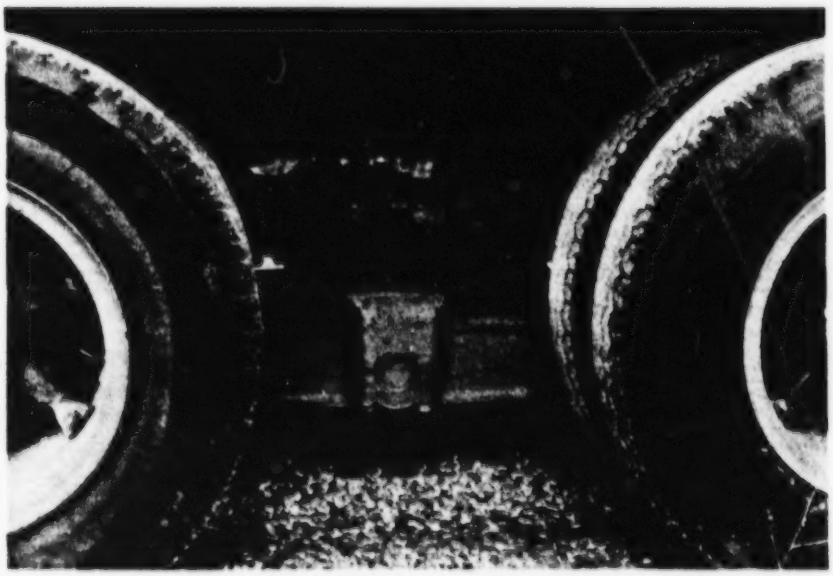


Figure 12/ Leaf Spring Suspension of TVI's Trailer

Figure 13/ Test Vehicle TV2

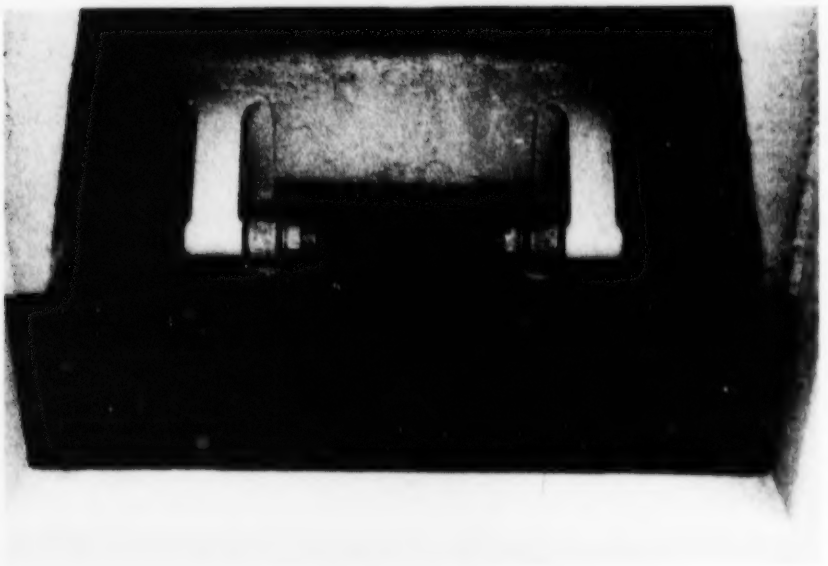


Figure 14/ Air Suspension of TV2's Trailer

Figure 15/ Test Vehicle TV3

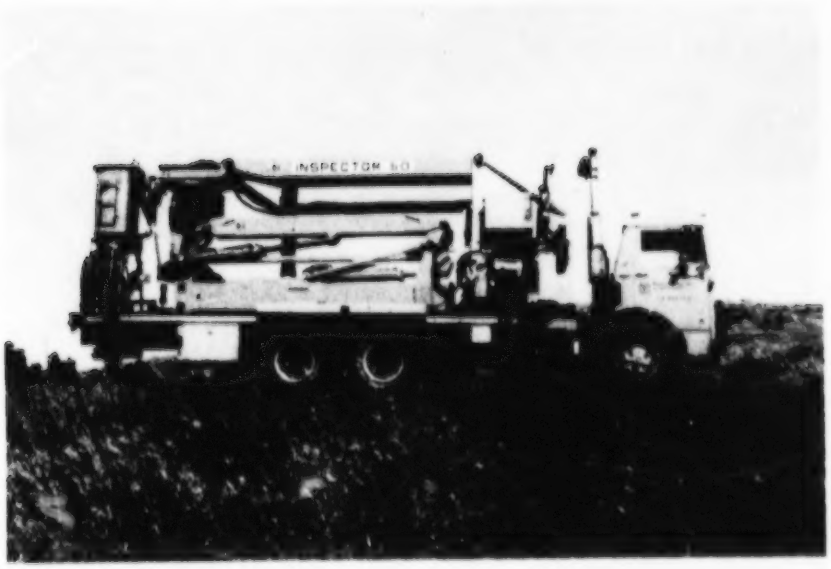


Figure 16/ Test Vehicle TV4

Figure 17/ Inspector 50 Extended

Figure 18/ Test Vehicle TV5

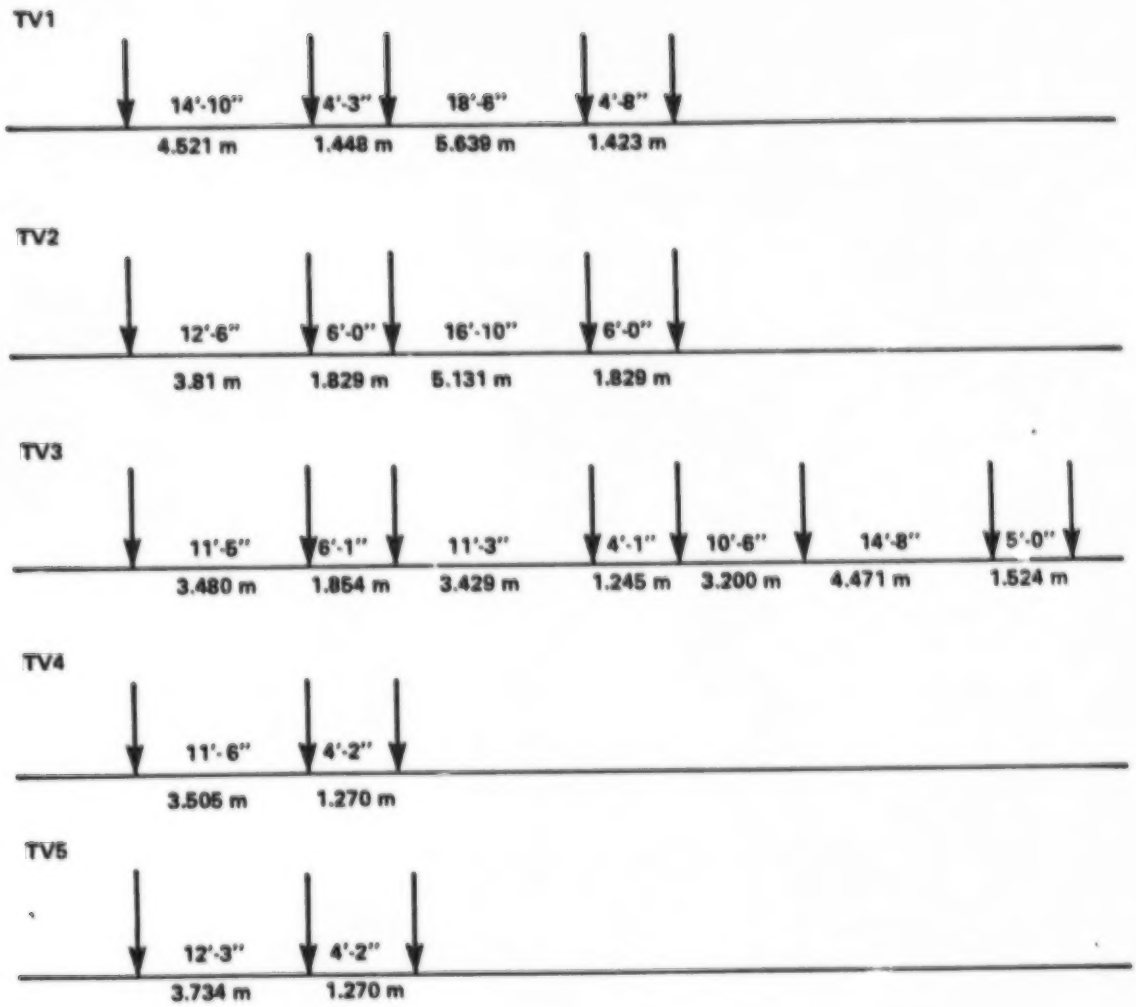


Figure 19/ Test Vehicle Dimensions

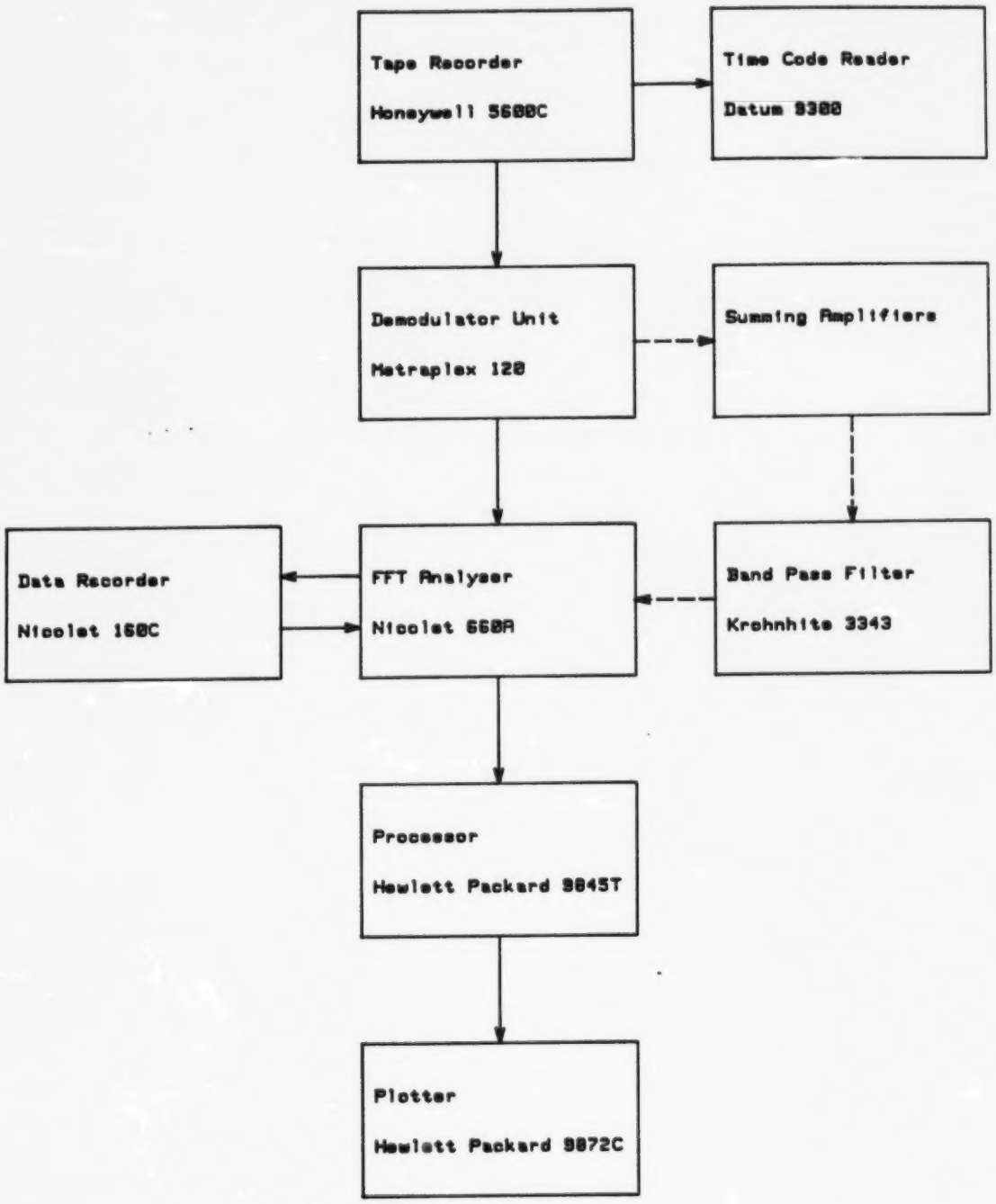


Figure 20/ Block Diagram of the Modal Analysis System

Figure 21/ View of Modal Analysis System

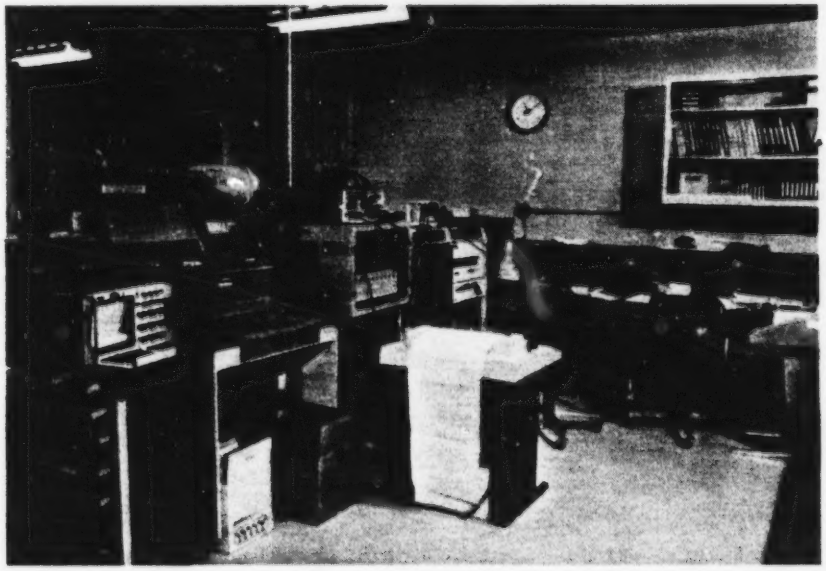


Figure 22/ View of Data Transcription System

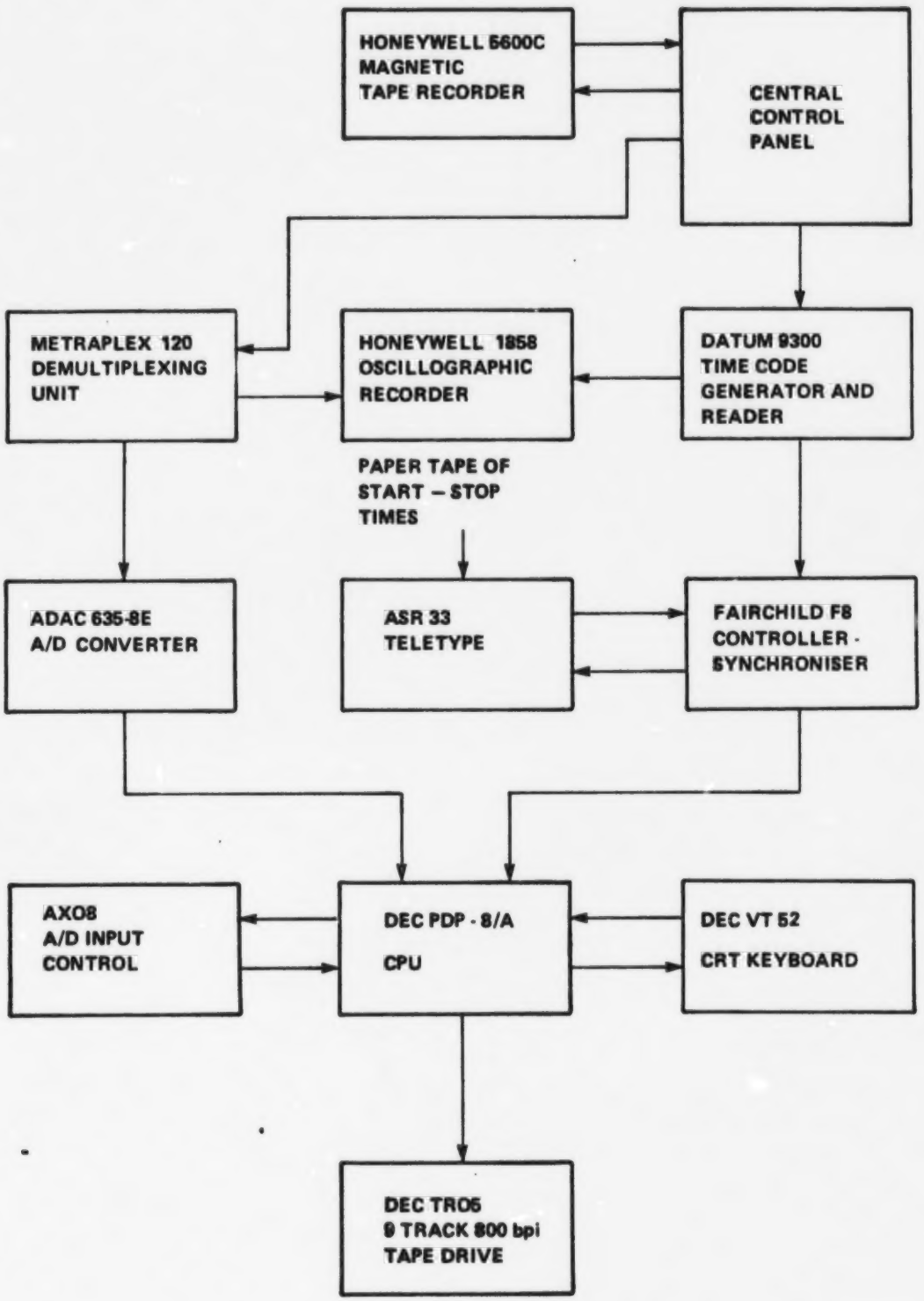


Figure 23/ Schematic of Data Transcription System

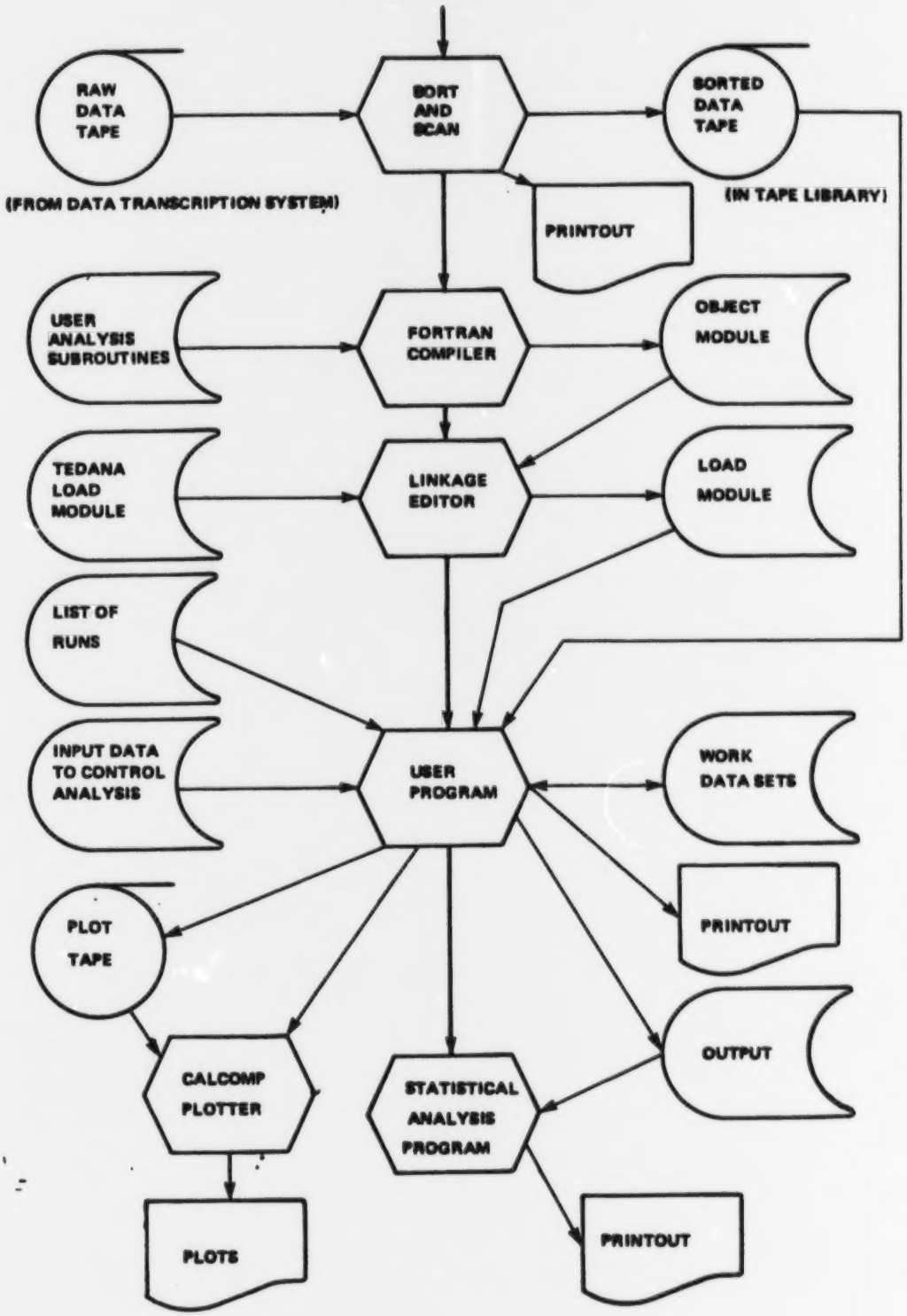
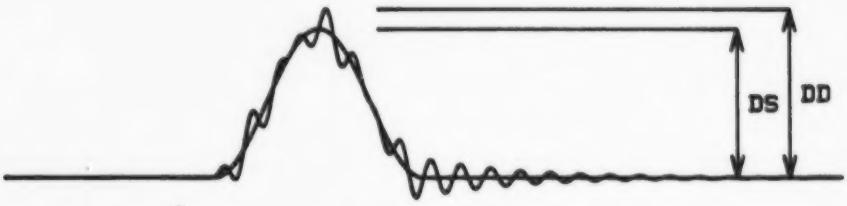


Figure 24/ Schematic of Digital Data Analysis

a/ Dynamic Response

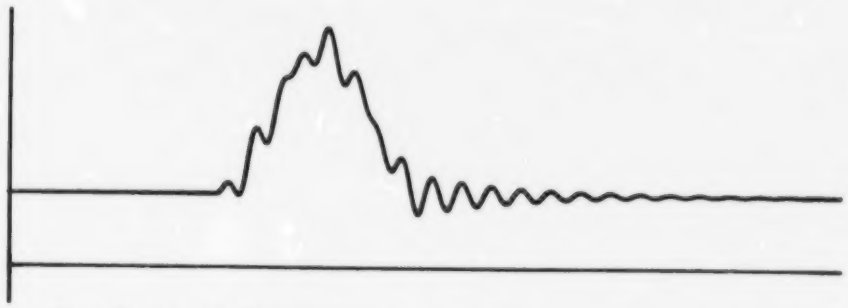
b/ Static Response

c/ Dynamic Component

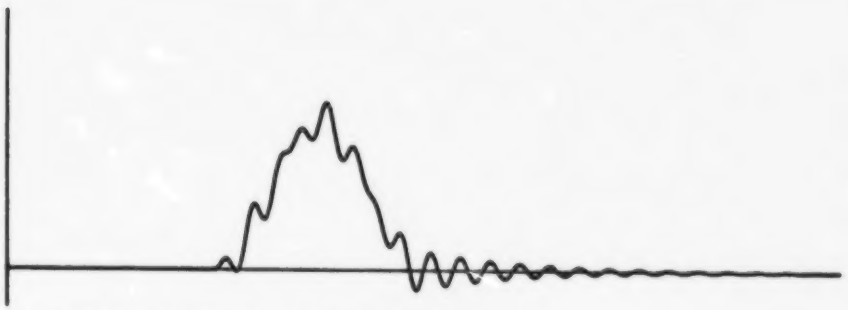


d/ Dynamic Amplification = (DD/DS)-1

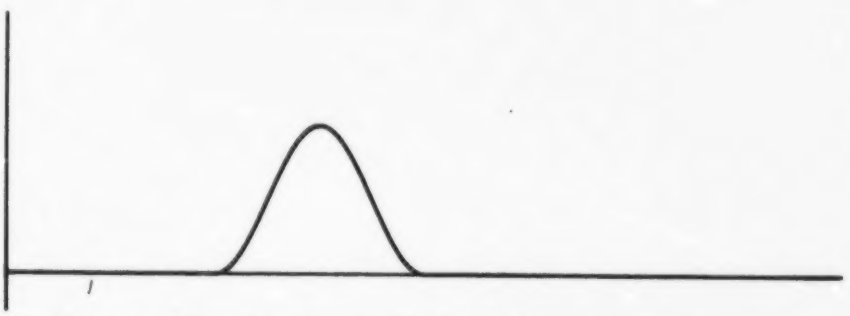
Figure 25/ Instrument Response Definitions



a/ Raw Dynamic Response

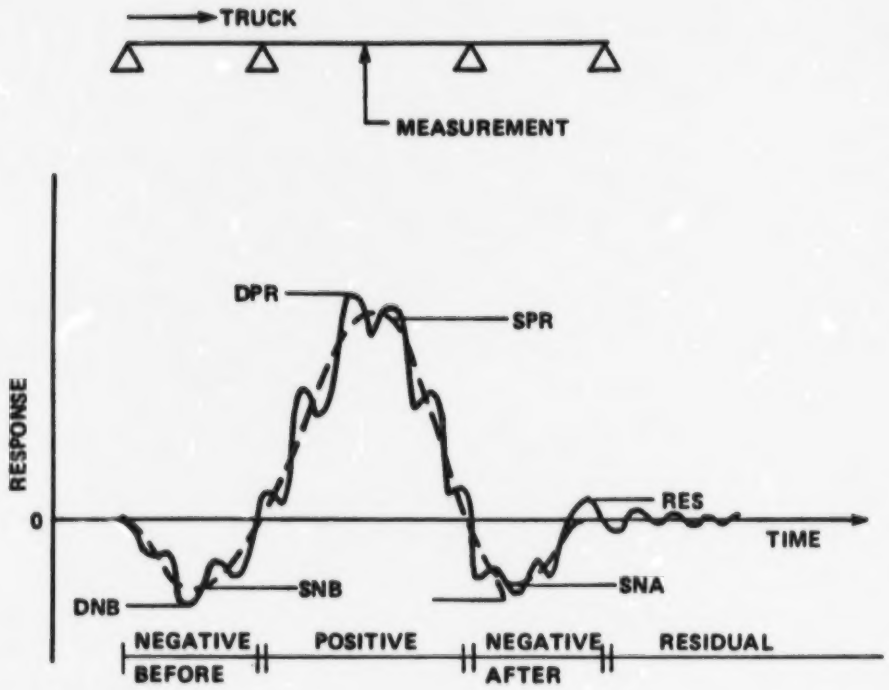


b/ Zeroed Dynamic Response

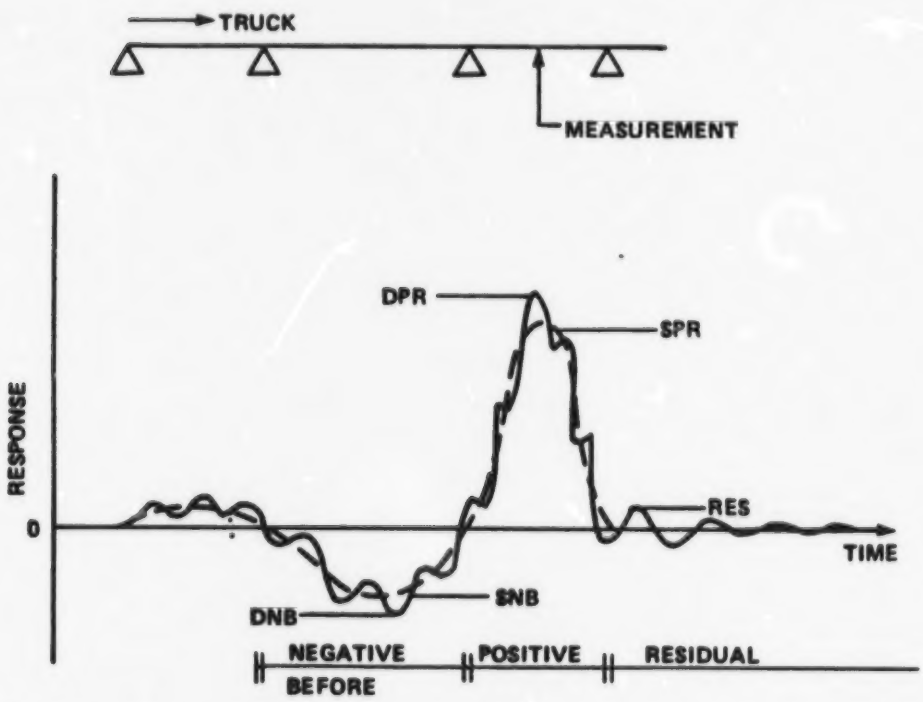


c/ Static Response from Filtered Dynamic Response

Figure 26/ Zeroing and Filtering



(a) MAIN SPAN RESPONSE



(b) SIDE SPAN RESPONSE

Figure 27/ Definition of Bridge Responses

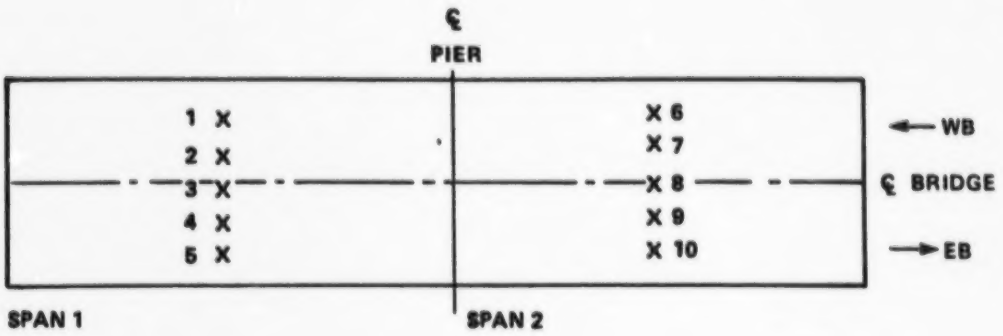


Figure 28/ Key Instruments

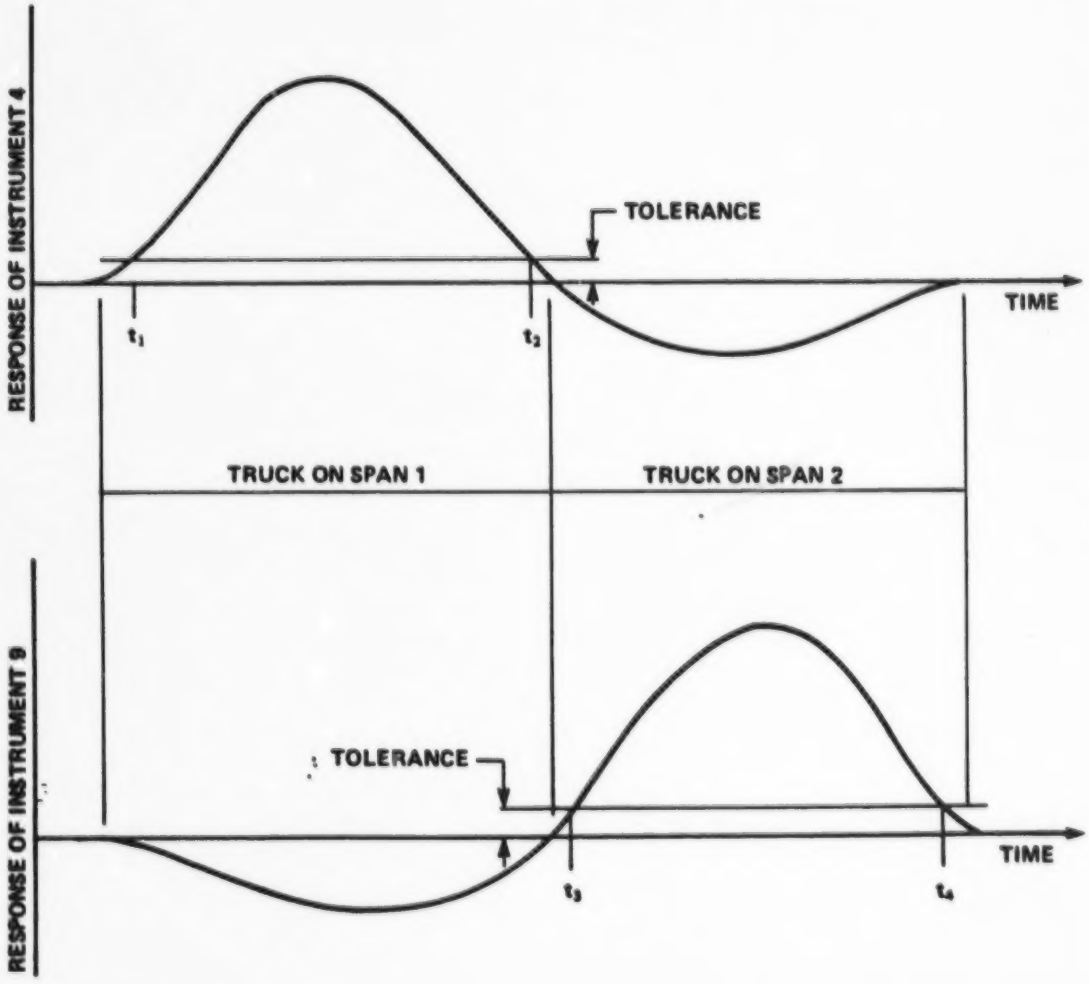


Figure 29/ Determination of Span Occupancy, Eastbound Truck Using Instrumentation Plan of Figure 28

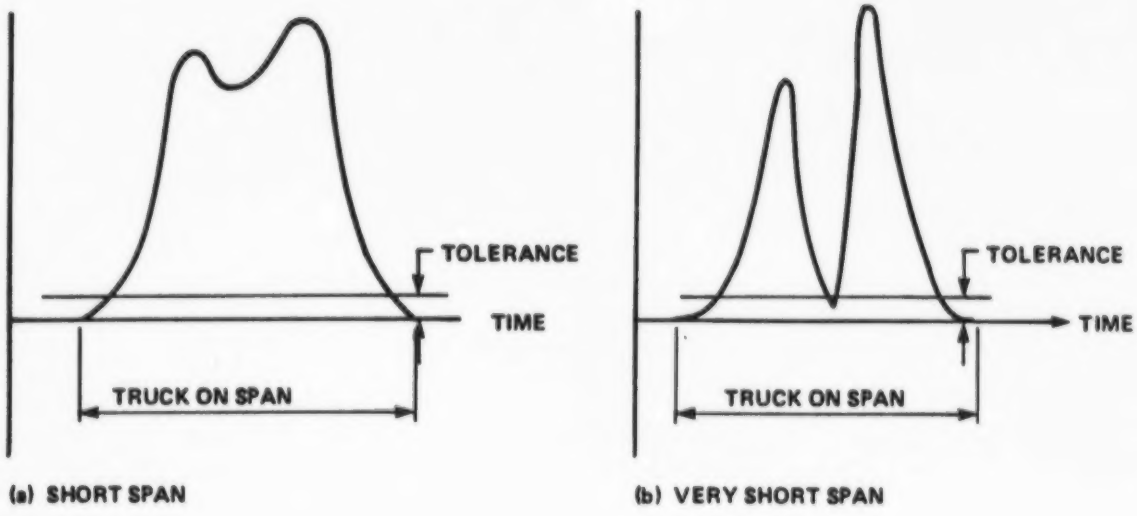


Figure 30/ Double Peak Response of Short Spans

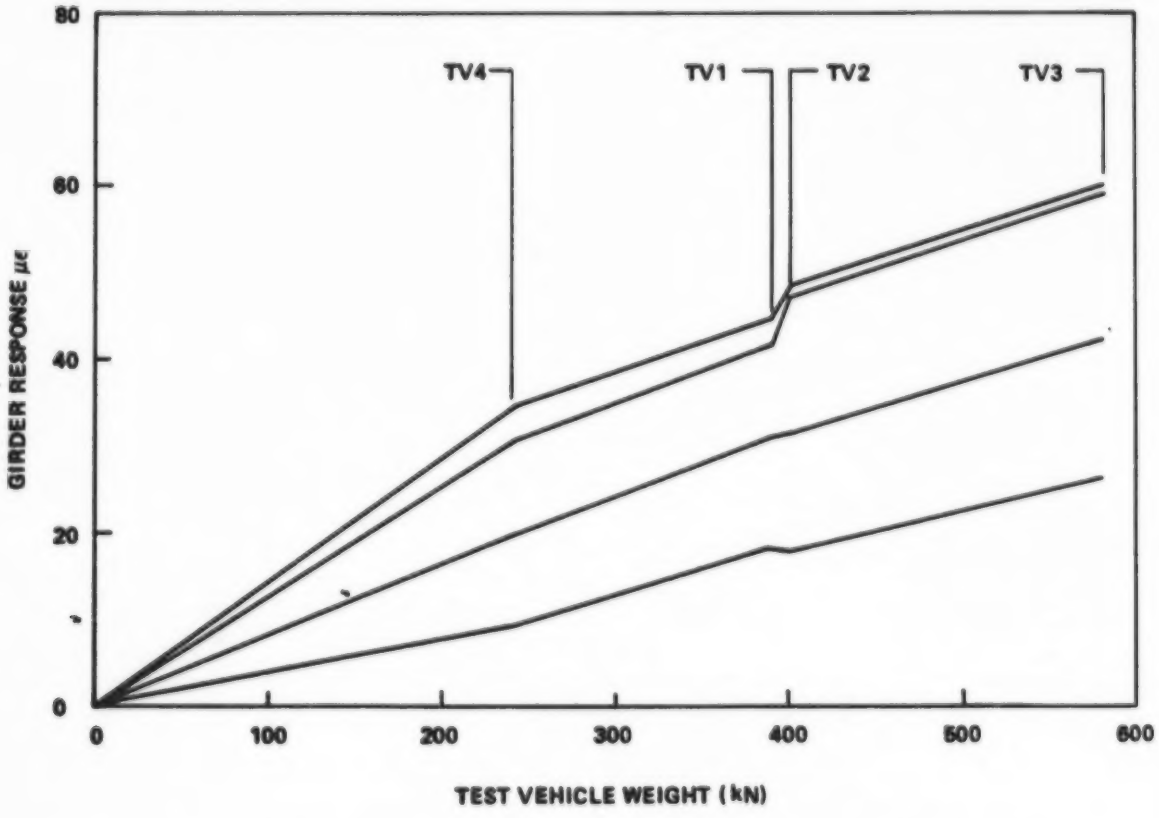


Figure 31/ Typical Transducer Responses vs Test Vehicle Weight from a Calibration Run

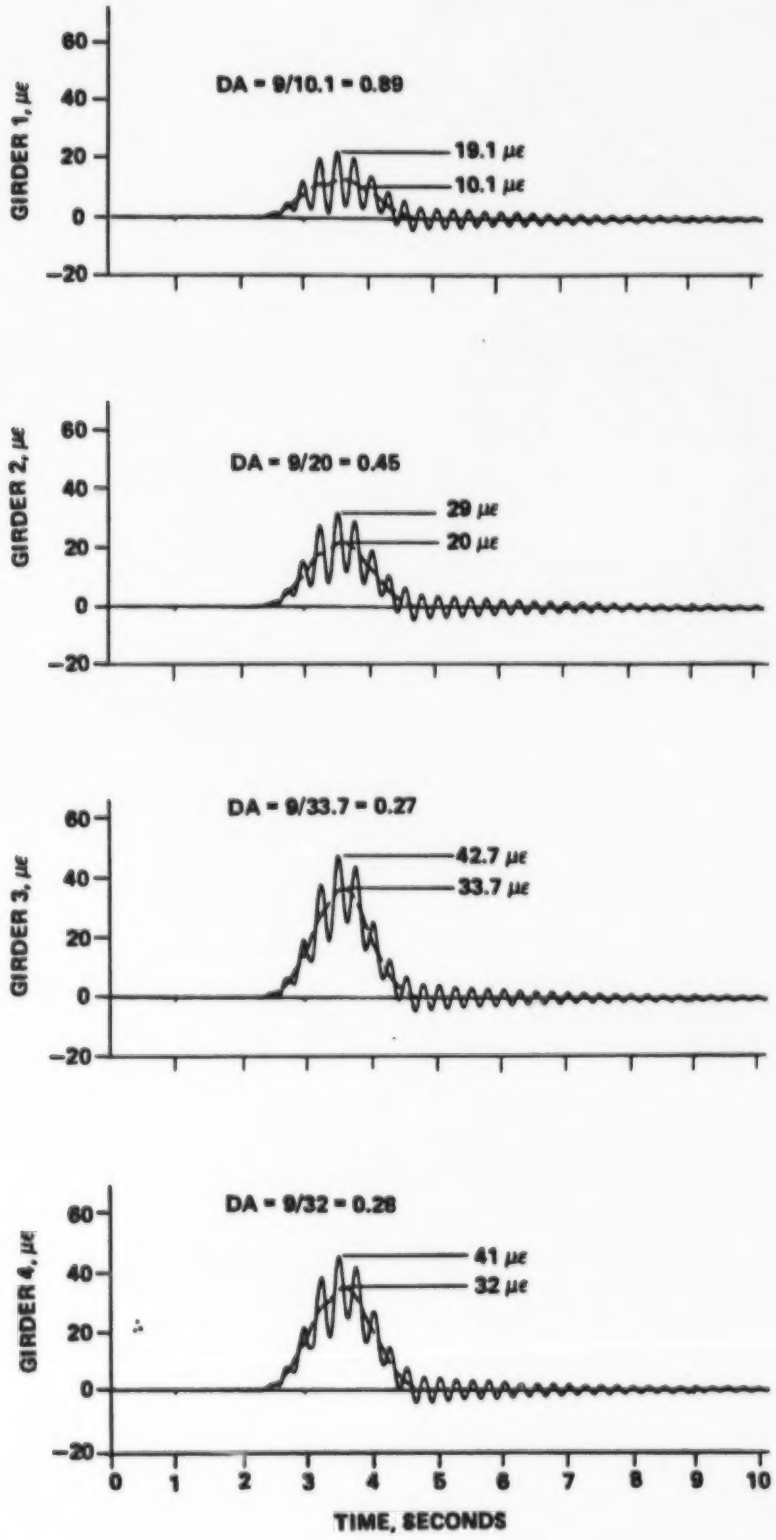


Figure 32/ Over-Estimation of Dynamic Amplification